

# SYNTHETIC, PHOTOPHYSICAL STUDIES OF 2-ALKENYL/ARYLBENZO-1,3,2-DIAZABOROLE COMPOUNDS AND THEIR PALLADIUM-CATALYSED CROSS-COUPLING REACTIONS

A dissertation Submitted to the University of KwaZulu-Natal for the Degree of  
Doctor of Philosophy in the School of Chemistry and Physics Pietermaritzburg  
Faculty of Science and Agriculture

By

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## **Thesis Declaration**

This is to certify that the experimental work and the results presented in this thesis are the original work of my own investigation carried-out at the School of Chemistry and Physics, University of KwaZulu-Natal, Pietermaritzburg campus and have not been submitted for any degree or diploma at any institution.

The work has been carried-out under the supervision of Professor R. S. Robinson.

Signed ..... Siphamandla Sithebe (Candidate)

Signed ..... Prof. Ross S. Robinson (Supervisor)

## Publication Declaration

The experimental work discussed, as well as the writing of the following articles has been performed by me under the supervision of Professor Robinson.

1. Palladium-Catalysed Cross-Coupling Reaction of Ultra-stabilised 2-arylbenzo-1,3,2-diazaborole with Aryl bromines: Direct Protocol for the Preparation of Biaryls, awaiting to be published in journal of organic chemistry.
2. 2-(1-Naphthyl)-1,3-dihydro-4,5-dimethyl-1,3,2-benzodiazaborole and 9'-bromo-2-(10'-anthryl)-1,3-dihydro-1,3,2-benzodiazaborole are awaiting to be submitted to the reviews for the publication to Acta E international journal.
3. 2-(3-Methoxyphenyl)-1,3-dihydro-1,3,2-benzodiazaborole. Accepted for publication, full reference, Robinson, R. S., Sithebe, S., Arkerman, M. P. (2012). *Acta Cryst. E* **68**, o2241.
4. The publication entitled 'Microwave-assisted Suzuki-Miyaura cross-coupling of alkenylbenzo-1,3,2-diazarolanes' has been accepted for publication in Tetrahedron. More than 75% of experimental work discussed in this article has been carried-out by me under the supervision of Prof. Ross S. Robinson. Full reference, Sithebe S., Hadebe, S.W., Robinson, R. S. *Tetrahedron*, **2011**, 67, 4277-4282.

All publications declared above have been included in text of this thesis as per faculty guidelines, and these studies represent the original work by the author and have not otherwise been submitted in candidature for any other degree.

I hereby certify that this statement is correct

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Siphamandla Sithebe (Candidate)

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Prof. Robinson (Supervisor)

## Abstract

This study was aimed at investigating the suitability of 2-alkyl/alkenylbenzo-1,3,2-diazaborolane compounds as potential nucleophilic coupling partners in the Suzuki-Miyaura cross-coupling reaction. A range of aryl bromides and iodides bearing electron-donating as well as electron-withdrawing substituents were reacted with 2-alkyl/alkenylbenzo-1,3,2-diazaborolane compounds under the influence of  $\text{Pd}(\text{OAc})_2/\text{PCy}_3$  combination. The cross coupling reaction afforded the desired products in yields ranging from 35% to 89% in less than 20 minutes. The catalytic system was found to be versatile and general tolerating a variety of functional groups including OMe,  $\text{NO}_2$ , OH, COOMe and  $\text{COMe}_2$ , thus demonstrating the suitability of 2-alkyl/alkenylbenzo-1,3,2-diazaborolane as coupling partners in the Suzuki-Miyaura cross-coupling methodology. The results from this study have been accepted for publication, full reference: (Sithebe, S., Hadebe, S. W., Robinson, R. S. *Tetrahedron*, **2011**, 67, 4277.)

Encouraged by the successful application of 2-alkyl/alkenylbenzo-1,3,2-diazaborolanes as coupling partners in the Suzuki-Miyaura (SM) cross-coupling reaction, we then extended our studies to investigate the synthesis and subsequent application of 2-arylbenzo-1,3,2-diazaborole analogues as potential coupling partners under the Suzuki-Miyaura cross-coupling reactions. The cyclocondensation of arylboronic acids with the corresponding 1,2-phenylenediamine afforded 2-arylbenzo-1,3,2-diazaboroles in yields ranging from 43% to 93%. The cross-coupling reaction of 2-arylbenzo-1,3,2-diazaboroles with the range of aryl bromides afforded the desired biaryl products in moderate to excellent yields ranging from 62% to 96%. Substrates bearing electron-withdrawing substituents were shown to be more reactive under these reaction conditions affording biphenyls in excellent isolated yields ranging from 83% to 96%. While our yields are comparable with the yields reported in literature, our reactions take only 10 minutes (!) compared to many hours of reflux as reported in the literature.

This project was also aimed at investigating the spectroscopic characteristics of 2-arylbenzo-1,3,2-diazaborole compounds by acquiring and studying their absorption and emission spectra. The data obtained revealed the lack of significant

solvatochromism for all the compounds in the ground state which is indicative of the presence of low dipole moments. These values were confirmed computationally which showed low calculated dipole in a range 0.1379-2.2773 D. In the excited state, all chromophores are influenced by the polarity of the solvent used pointing to the presence of solvatochromism. The introduction of a donor group such as thioether (MeS) and the introduction of bromine atom, on the  $\pi$ -system, have proven beneficial for the emission maxima of the species investigated.

The extension of  $\pi$ -conjugation length at the 2-position of these species and the methylation at the backbone of 1,3,2-benzodiazaborolyl group leads to bathochromic shifts of the emission maxima, which in turn lead to large Stokes shifts of up to 11000  $\text{cm}^{-1}$ . Alternatively, the formal insertion of the phenyl spacer between the naphthyl ring and the 1,3,2-benzodiazaborolyl group does not have any influence on the photophysical properties of these compounds.

The HOMOs of all the chromophore are purely represented by the 1,3,2-benzodiazaborolyl group except for anthracenyl-functionalised benzo-1,3,2-diazaborolane compounds in which the HOMO are located on the  $\pi$ -system with no contribution of the vacant  $2p_z$ -orbital of the boron atom. The large Stokes shifts and significant solvatochromism displayed by these compounds are suggestive of the potential application in organic light emitting diodes (OLED) as emitters. The results from this study have been drafted for publication in Dalton Transition.

## List of Abbreviations

Ar	aryl
Ac	acetyl
9-BBN	9-borabicyclo-[3,3,1]-nonane
Bu	butyl
BuLi	butyllithium
B(OMe) <sub>3</sub>	trimethylborate
B(Sia) <sub>2</sub>	disiamylborane
bp	Boiling point
CuI	Cupper (I) iodide
d	doublet
DCM	dichloromethane
DEPT	Distortionless enhancement bipolarization transfer
dil. HCl	diluted hydrochloric acid
DFT	Density functional theory
DMSO	Dimethyl sulfoxide
EI	Electron impact
equiv	equivalent
B3LYP	3-parameter hybrid Becke exchange/Lee- Yang-Parr correlation functional
°C	Degree Celsius
calcd	calculated
cm <sup>-1</sup>	wave number
cod	1,5-cyclooctadiene
concd	concentrated
concn	concentration
ESI	Electro spray ionisation
Et	ethyl
g	gram (s)
GC	gas chromatography

h	hour(s)
HOMO	highest occupied molecular orbitals
HRMS	high-resolution mass spectroscopy
HSQC	heteronuclear single quantum correlation
Hz	hertz
COSY	correlation spectroscopy
$\delta$	chemical shift in part per million downfield from tetramethylsilane
LUMO	lowest unoccupied molecular orbital
M	molar
$M^+$	parent molecular ion
IR	infra red
$J$	coupling constant
lit.	literature value
q	quartet
Me	methyl
mol	moles
mp	melting points
$m/z$	mass-to-charge ratio
s	single
t	triplet
Ph	phenyl
ppm	part(s) per million
Pr	propyl
<i>i</i> -Pr	isopropyl
THF	tetrahydrofuran
UV	ultraviolet
vis	visible

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# Chapter One

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## 1. General Introduction

Carbon-carbon cross-coupling reactions are one of the most important and well developed methods due to their widespread applications in organic synthesis.<sup>1</sup> The importance and the versatility of these coupling methodologies is evident with the substantial growth in terms research inputs which consequently leads to a larger number of publications and patents witnessed in the past decade.<sup>2,3</sup> Suzuki-Miyaura cross-coupling, Heck, Sonogoshira and Negishi cross-coupling reactions are the most popular and the most applied coupling reactions within organic chemistry. Due to their importance, these reactions have been used extensively in the synthesis of pharmaceuticals,<sup>4</sup> natural products components, liquid crystals<sup>5</sup> and molecular materials.<sup>6</sup>

Amongst them, the Suzuki-Miyaura cross-coupling methodology is the most developed, extremely powerful and versatile tool for the construction of new carbon-carbon bonds.<sup>7</sup> The versatility of the Suzuki-Miyaura cross-coupling reaction is largely inherited from the non-toxicity of the nucleophilic coupling partners (boronic acids), the generality as well as the mildness of the reaction conditions mostly used in this reaction.<sup>7</sup>

During the final quarter of the 19<sup>th</sup> century, the Suzuki-Miyaura cross-coupling reaction only accommodated the C<sub>(aryl)</sub>-C<sub>(aryl)</sub> bond formation, i.e. the construction of C<sub>alkyl</sub>-C<sub>alkyl</sub> has been reported by many research groups to be problematic due to the difficulty encountered during the transmetallation step.<sup>8</sup> For this reason, much of the previous effort on the Suzuki-Miyaura

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<sup>1</sup> Da Costa, D.P., Nobre, M.S. *Tetrahedron Lett.* **2013**, 54, 4582.

<sup>2</sup> Seechurn, C. C. C. J., Kitching, M. O., Colacot, T. J., Sniekus, V. *Angew. Chem. Int. Ed.* **2012**, 15, 5062.

<sup>3</sup> Li, H., Seechurn, C. C. C. J., Colacot, T. J. *ACS Catal.* **2012**, 2, 1147.

<sup>4</sup> Toghiani, S. M. T., Fatunsin, O., Villinger, A., Langer, P. *Tetrahedron Lett.* **2011**, 52, 3732.

<sup>5</sup> Gou, M. P., Jian, F. F., He, R. *Tetrahedron Lett.* **2006**, 47, 2033.

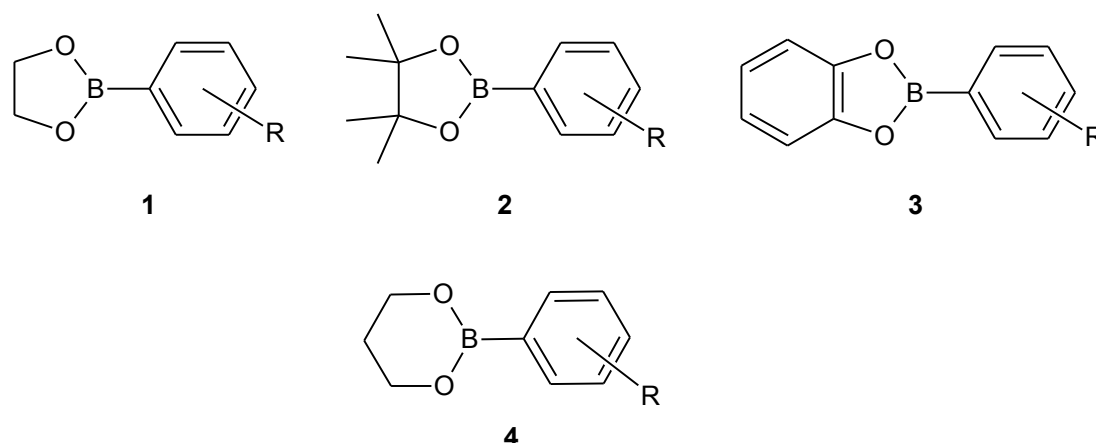
<sup>6</sup> Wang, K., Yi, T., Yu, X., Zheng, X., Fu, H., Chen, H., Li, R. *Appl. Organomet. Chem.* **2012**, 26, 342.

<sup>7</sup> Miyaura, N., Suzuki, A., *Chem. Rev.* **1995**, 95, 2457.

<sup>8</sup> Rudolph, A., Lautens, M. *Angew. Chem., Int. Ed.* **2009**, 48, 2656.

cross-coupling reaction has focused exclusively on improving previous reaction conditions and developing new metal/ligands system that promote the formation of new C<sub>alkyl</sub>-C<sub>alkyl</sub> and expand the reaction scope. This has resulted in tremendous improvements being achieved such as conducting the reaction in water at room temperature.

Despite these improvements, the Suzuki-Miyaura cross-coupling reaction is only limited to boronic acids as coupling partners. Only a few research groups have directed their aims towards improving the generality of the Suzuki-Miyaura cross-coupling reaction by expanding the range of organoboranes that can be used as nucleophilic coupling partners.<sup>9</sup> We are aware of organoboronate esters which have been reported to participated in the Suzuki-Miyaura cross-coupling reaction, these reagents are both air and moisture sensitive and are also costly which automatically rules them out of the equation (**Figure 1**). In addition, these reagents have been reported to be less reactive than boronic acids.<sup>10</sup>



**Figure 1: Arylorganoboronate esters.**

Several potassium aryl- and 1-akenyltrifluoroborates have been reported to participate in the Suzuki-Miyaura cross-coupling reaction as coupling partners.<sup>11</sup> Potassium trifluoroborates have been reported to be more convenient in terms of air and moisture stability when

<sup>9</sup> Flaherty, A., Trunkfield, A., Barton, W. *Org. Lett.* **2005**, 7, 4975.

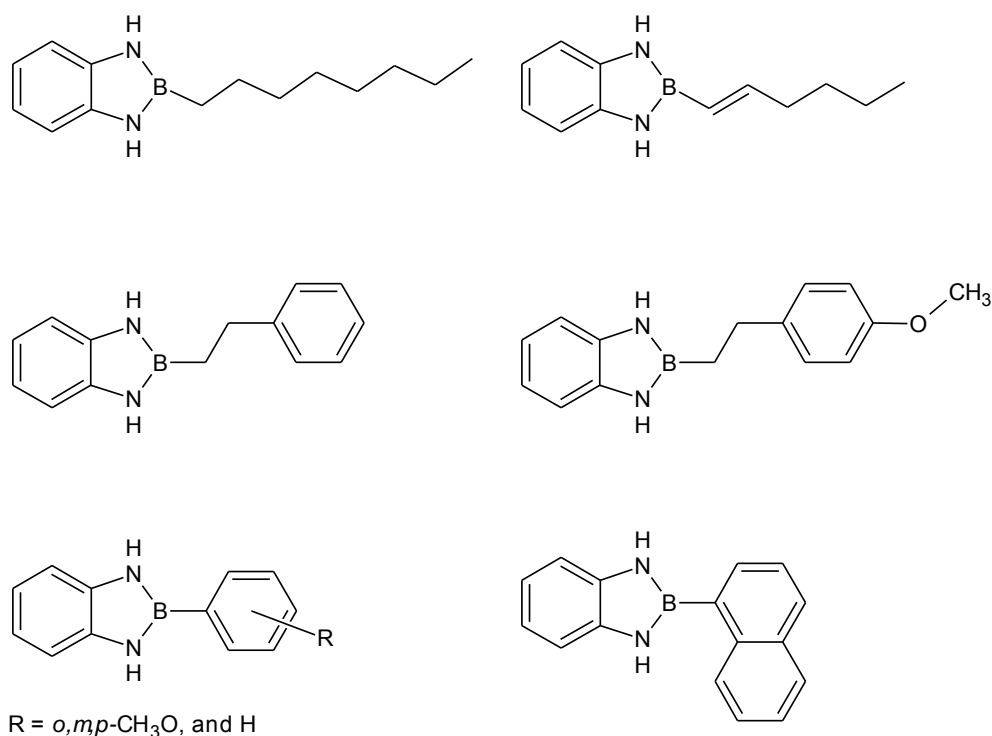
<sup>10</sup> Murphy, M. J., Tzschucke, C. C., Hartwig, J. F. *Org. Lett.* **2007**, 9, 757.

<sup>11</sup> Molander, A. G., Ito, T. *Org. Lett.* **2001**, 3, 396.

compared to the corresponding organoboranes and boronic esters.<sup>12</sup> It is believed that the enhanced stability and a greater nucleophilicity of potassium trifluoroborates play a significant role in their reactivity; hence these compounds make potentially valuable starting material for the Suzuki-Miyaura cross-coupling reaction. However, one disadvantage of using potassium fluoro-borates nucleophiles is their reluctance to couple to aryl halide.<sup>13</sup>

The lack of intense research to find alternative organoboron compounds that can react as nucleophilic coupling partners in the Suzuki-Miyaura cross-coupling reaction prompted our investigation into the palladium-catalysed Suzuki-Miyaura cross-coupling reaction of 2-(aryl/alkenyl/alkyl)benzo-1,3,2-diazaborolanes compounds with aryl halides.

Herein we report the synthesis of substituted ultra-stabilised benzo-1,3,2-diazaborolane compounds and their coupling reactions. Chapter two and chapter four focus on the synthesis of 2-(aryl/alkyl/alkenyl)-benzylbenzo-1,3,2-diazaborolane compounds (**Figure 2**) and their coupling reactions with aryl halides bearing electron-donating, electron withdrawing as well as electron-neutral substituents.



**Figure 2: Synthesized 2-(aryl/alkenyl/alkyl)-benzo-1,3,2-diazaborole compounds**

<sup>12</sup> Batey, R. A., MacKay, D. B., Santhakumar, V. *J. Am. Chem. Soc.* **1999**, 121, 5075

<sup>13</sup> Littke, A. F., Chaoyang, D., Fu, G. *J. Am. Chem. Soc.* **2000**, 122, 4020



Chapter three focuses on the evaluation of electronic structures of the synthesised compounds by acquiring and studying their (i) UV/Visible absorption spectra and (ii) Luminiscence (emission spectra). DFT calculations of the synthesized compounds were also be performed in order gain solid understanding of the nature of frontier orbitals, the electron transaction within the molecules and the energies associated with each transaction.

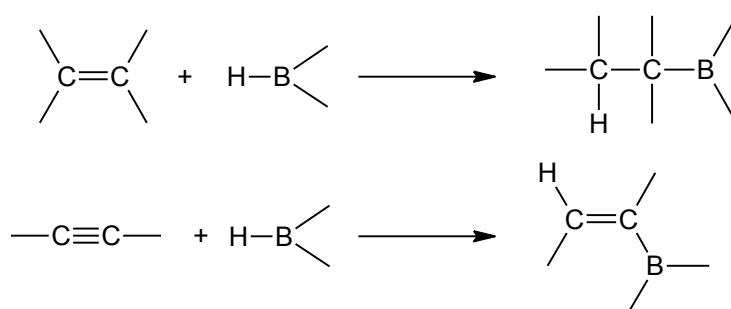
# Chapter Two

## 2. Introduction

### 2.1 Hydroboration

A search for a methodology that converts olefins to synthetically useful organic intermediates, which in turn can readily be transformed into different products, has long been and is still the subject of considerable interest in organic chemistry.<sup>1</sup> Traditionally, the conversion of olefins to synthetically useful intermediates involved the reaction of various organometallic reagents with boron esters or boron halides to produce the corresponding organoborane derivatives. However, the instability of organometallic reagents towards air and moisture introduced drawbacks in the application of this method as synthetic route to organoboranes.<sup>1</sup>

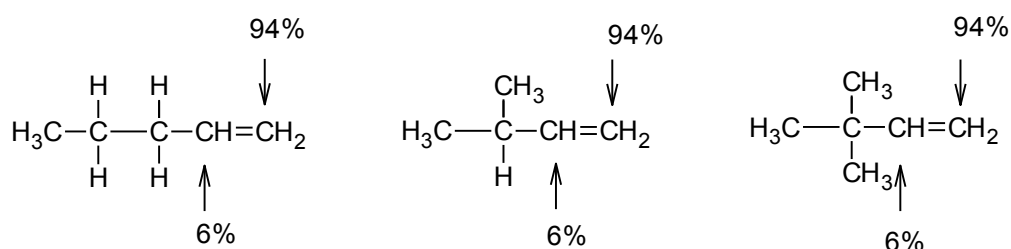
It wasn't until the mid 1950s that the conversion of olefins to synthetically useful organoborane compounds was a smooth and high yielding process.<sup>2</sup> In 1956 Brown and Subba Rao were the first researchers to report and demonstrate that olefins could rapidly be converted to organoboranes when reacted with diborane in ethereal solvents (**Figure 3**).<sup>2</sup> The term 'Hydroboration' was born when Brown and Subba Rao realised that the conversion of olefins into organoboranes involves rapid and quantitative insertion of the boron-hydrogen bond to the unsaturated carbon-carbon double or triple bonds of olefins (Scheme 2.1).<sup>2</sup>



**Figure 3: Schematic representation of hydroboration reaction**

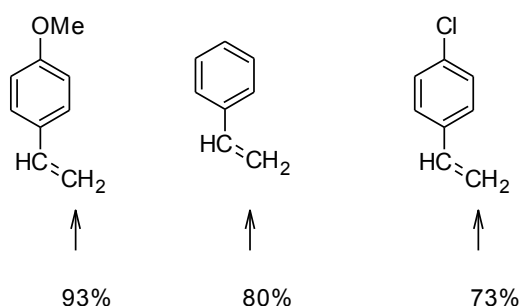
After these discoveries, numerous unsaturated organic compounds were subjected to hydroboration with the aim of exploring the scope and the limitations of this newly discovered methodology. Extensive studies conducted by Brown and Zweifel revealed

that a vast majority of unsaturated organic compounds including, olefins, dienes, acetylenes, substituted and unsubstituted styrenes are capable of undergoing hydroboration (at room temperature) when treated with borane solution in less than an hour. However, even though numerous unsaturated organic compounds are hydroborated when treated with diborane at room temperature, preliminary observation indicated that the placement of the boron atom across the double bond was the same in almost all olefins with different steric demand. For example, the hydroboration of unsymmetrical olefins proceed to insert the boron atom preferentially on the carbon containing the most hydrogen atoms (i.e. the less sterically hindered of the two carbons).<sup>3</sup>



**Figure 4: The distribution of the boron atom across the double bond**

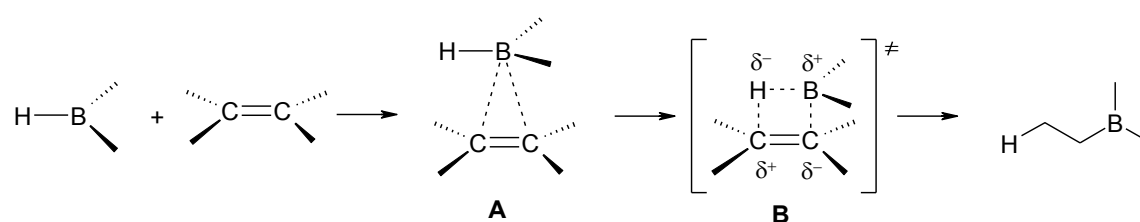
It has been shown, however, that the phenyl group as well as the substituents on the phenyl ring has significant influence in controlling the placement of the boron atoms across the double bond. For example, the hydroboration of styrene leads in 80% placement of the boron atom at the terminal carbon whereas the hydroboration of methoxy and chloro substituted styrene proceeds to place 93% and 73% of the boron atom at the  $\alpha$ -positions, respectively (**Figure 5**).<sup>3</sup>



**Figure 5: The distribution of the boron atom across the double bond.**

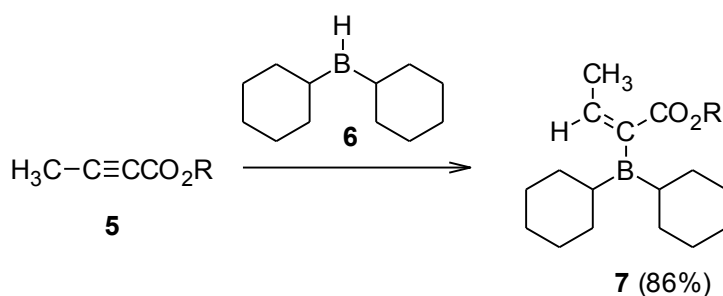
The growing importance of hydroboration reactions soon demanded comprehensive studies on factors that govern the distribution of the boron atom across the double

bond. As a consequence, numerous experiments were conducted and their results revealed that the direction of the addition is strongly influenced by steric and electronic factors. From these observations, the authors proposed a mechanism which showed that the addition of the boron-hydrogen bond (B–H), across multiple bonds of olefins, proceeds *via* the formation of a four centred-transition state complex, with the distribution of boron atom greatly controlled by the polarisation of B–H bond (**Figure 6**).<sup>4</sup>



**Figure 6: Accepted mechanism for the hydroboration.**

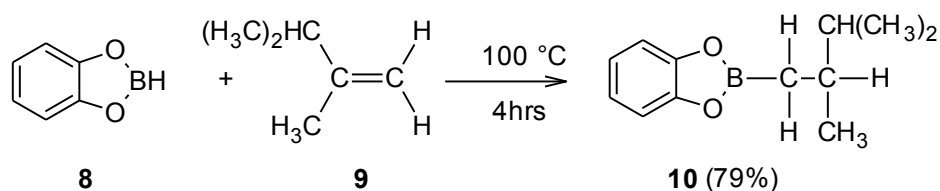
During the first four years after the proposal of the hydroboration mechanism by Brown,<sup>4</sup> considerable effort was devoted towards developing new hydroborating reagents that could selectively distribute the boron atom at the terminal carbon of the double bond. As a consequence, numerous alkylated hydroborating agents were unveiled including hexylborane, disiamylborane, 9-BBN and diisopinacampheylborane. These reagents were reported to selectively place the boron atom at the α-carbon with no trace of the internal hydroboration product being formed. For example, in 1971 Zweifel *et al.*<sup>5</sup> reported that dicyclohexylborane (**6**) hydroborate sterically hindered internal alkynes (**5**) to the corresponding vinyldicycloborane (**7**) in excellent yields (**Scheme 1**).<sup>5</sup>



**Scheme 1**

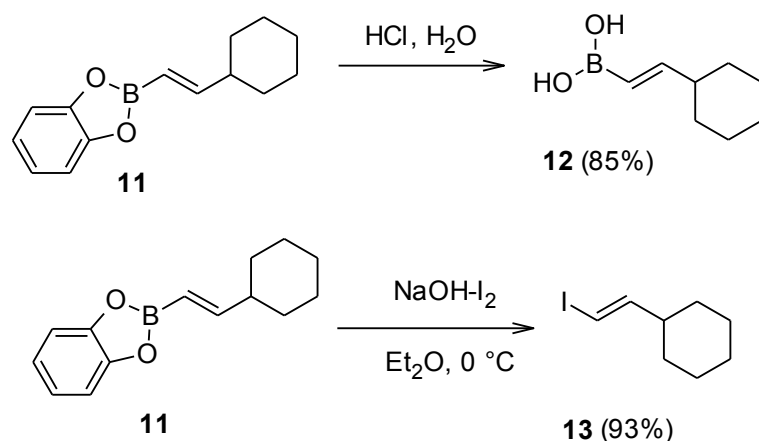
The development of alkylborane reagents as regioselective monohydroborating reagents made researchers realise that the use of hydroborating agents with sterically

demanding structures was the key to place regioselectively the boron atom at the less hindered carbon of the double bond. These findings eventually shifted their research focus towards the investigation of heterosubstituted boranes as hydroborating agents. In 1971, Gupta and co-worker were the first to report the preparation and the use of heterosubstituted boranes (catecholborane) as a hydroborating agent. This reagent was reported to readily hydroborate olefins cleanly to the corresponding alkyl alkenylboronic esters (**Scheme 2**).<sup>6</sup>



**Scheme 2**

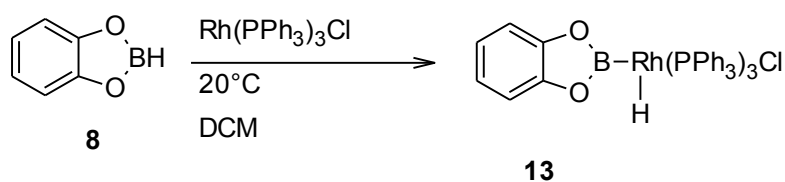
Since its discovery, catecholborane (**8**) has been utilised for the conversion of unsaturated organic compounds to the corresponding organocatecholboronic esters (**11**). One of the most important applications of organocatecholboronic esters (**11**) is their acid hydrolysis to the corresponding boronic acids (**12**) or their conversion to iodinated alkenes (**13**) (**Scheme 3**). Both products are known to participate in metal catalysed cross-coupling reactions such as the Suzuki-Miyaura cross-coupling reactions which will be discussed in details in section 2.2 below.<sup>7</sup>



**Scheme 3**

## 2.2 Metal-Catalysed Hydroboration

The foundation of metal-catalysed hydroboration reaction was discovered in 1975 when Kono and Ito discovered that the treatment of Wilkinson catalyst ( $\text{Rh}(\text{PPh}_3)_3\text{Cl}$ ) with the solution of catecholborane (**8**) in dry solvent leads to oxidative addition of the boron-hydrogen bond of catecholborane (**8**) to the rhodium metal centre (**Scheme 4**).<sup>8</sup> This observation suggested the usefulness of Wilkinson catalyst in the hydroboration reaction, however, almost a decade past before Wilkinson catalyst was recognised as potential catalyst for the hydroboration reactions.



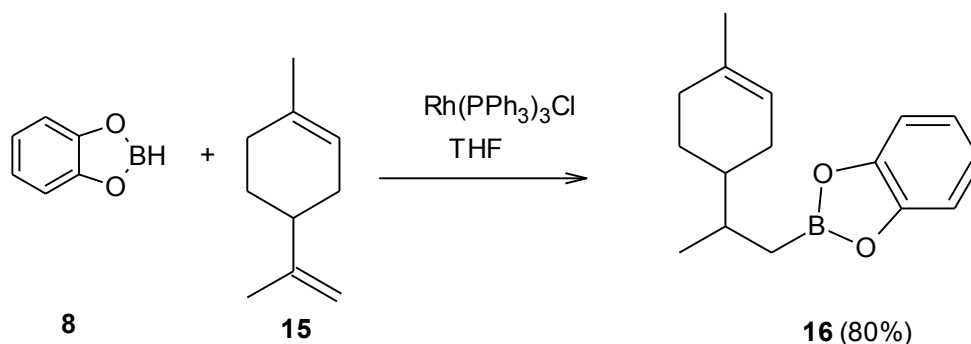
**Scheme 4**

In 1985, Manning and Nöth were the first researchers who demonstrated and reported that catecholborane hydroborate certain alkenes, at room temperature, in only 20 minutes\* under the influence of  $\text{Rh}(\text{PPh}_3)_3\text{Cl}$ .<sup>9</sup> After these discoveries, several alkenes were screened in order to explore the scope and direct effects of this newly discovered methodology.

During the screening, the authors reported that numerous olefins are hydroborated with catecholborane under the influence of  $\text{Rh}(\text{PPh}_3)_3\text{Cl}$  catalyst. Similar to the uncatalysed hydroboration reactions, the catalysed hydroboration was also shown to be sensitive to the steric effect of the olefinic substrates used. For example, Manning and Nöth presented that the catalysed hydroboration of limonene (**14**) preferentially place the boron atom at the less hindered carbon-carbon double bond of this molecule to produce product (**15**) (**Scheme 5**).

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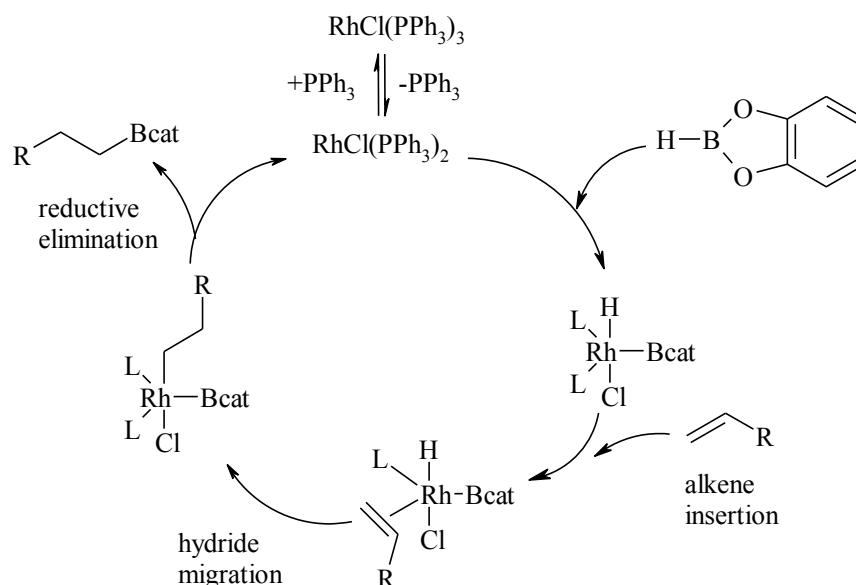
\* A reaction which normally requires 100 °C for 4 hour for completeness



**Scheme 5**

The regioselectivity of  $\text{Rh(PPh}_3)_3\text{Cl}$  catalysed hydroboration reaction was demonstrated by a number of researchers to be much superior relative to the regioselectivity achieved by the uncatalysed hydroboration reaction. The  $\text{Rh(PPh}_3)_3\text{Cl}$  catalysed hydroboration of styrene, for example, proceeded to place 99% of the boron atom at the  $\beta$ -carbon compared to only 20% achieved by the uncatalysed hydroboration.<sup>10</sup>

To gain an accurate and deep understanding of the reaction, Manning and Nöth proposed mechanism in which the initial step involved the oxidative addition of catecholborane to the central rhodium metal. This step is followed by the coordination of the olefin and subsequently the hydride migration. Finally, the reductive elimination step regenerates the catalyst and produces the desired boronic ester (**Figure 7**).<sup>9</sup>

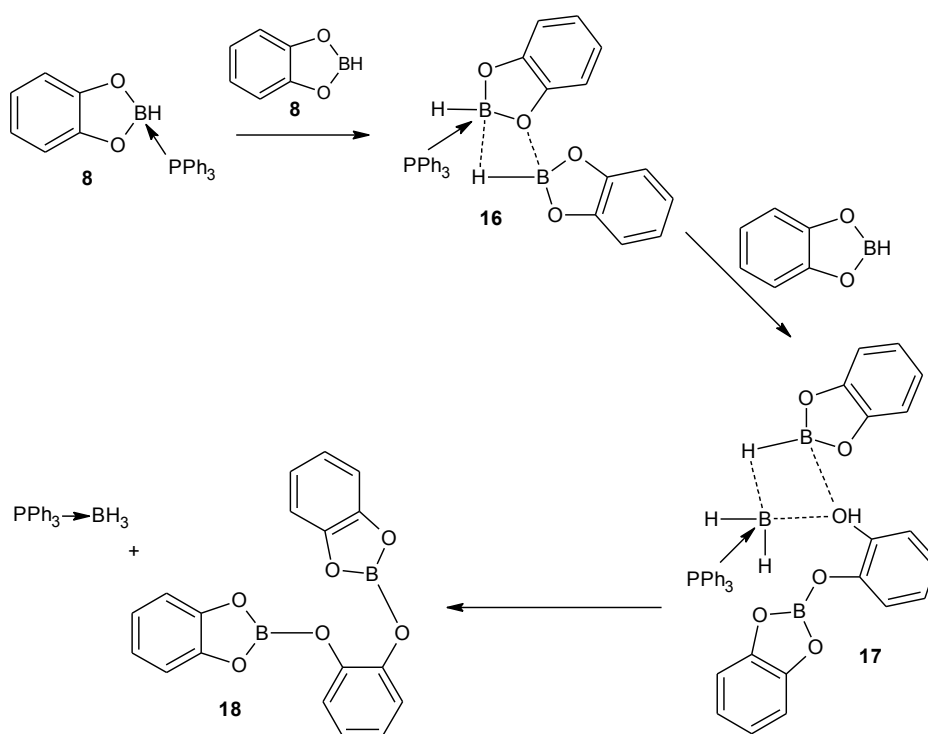


**Figure 7: Accepted rhodium catalysed hydroboration of terminal alkenes**

To account for the regioselectivity observed in  $\text{Rh}(\text{PPh}_3)_3\text{Cl}$  catalysed hydroboration reaction, Evans and co-workers studied, in details, the mechanism of this reaction using deuterium labelling. According to Evans and co-workers, the mechanism initially presented by Manning and Nöth (Scheme 2.7) was rather more simple and straight forward, and does not address the routes for the formation of other products (i.e. its only accounts for the formation of terminal product). The deuterium labelling studies revealed that as many as seven different products are formed during this process, which clearly contrast with the mechanism proposed by Manning and Nöth.<sup>10,11</sup>

Shortly after these findings by Evans and co-workers, extensive studies on  $\text{Rh}(\text{PPh}_3)_3\text{Cl}$  catalysed hydroboration of olefins conducted by Burgess *et al.*<sup>12</sup> revealed that the low enantioselectivity achieved by this reaction was greatly attributed to the decomposition (disproportionation) of catecholborane (**8**) during the reaction.<sup>12</sup> A year later, Westcott *et al.*<sup>13</sup> confirmed the observation made by Burgess *et al.*, and they proposed a disproportionation mechanism in order to explain factors which lead to the degradation of catecholborane (**8**). According to Burgess *et al.*<sup>12</sup> the degradation of catecholborane is attributed to the formation of thermodynamically stable tris-(catecolato) diboron ( $\text{Cat}$ )<sub>3</sub>B<sub>2</sub> product (**18**) (Scheme 6).



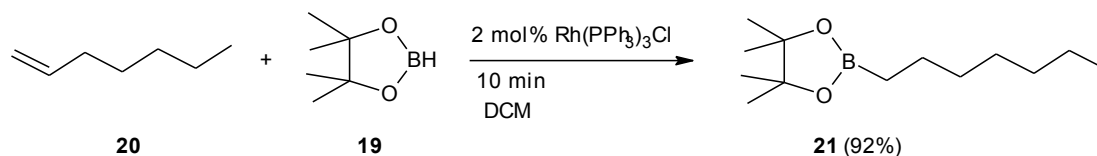


**Scheme 6**

The disproportionation mechanism proposed by Westcott *et al.*<sup>13</sup> revealed that the electron rich triphenylphosphine ligand (PPh<sub>3</sub>) initiates the process by inductively donating its pair of electrons to the electron-deficient boron atom of catecholborane.<sup>13</sup> This effect weakens the boron-oxygen bond, which in turn, facilitates the coordination of the second catecholborane molecule. The addition of the third catecholborane molecule produces borane gas (BH<sub>3</sub>) and the disproportionation tris-(catecholato) diboron (Cat)<sub>3</sub>B<sub>2</sub> product **A** (Scheme 2.8).<sup>13</sup> From the mechanistic investigation, the authors concluded that the disproportionation of catecholborane is greatly facilitated by the lack of sufficient electron density donated to vacant 2p<sub>z</sub>-orbital of the boron atom. The electron density on each oxygen atoms has been reported to be unavailable to interact with the vacant 2p<sub>z</sub>-orbital of the boron atom due to their participation in the aromatic ring of catecholborane.<sup>13</sup>

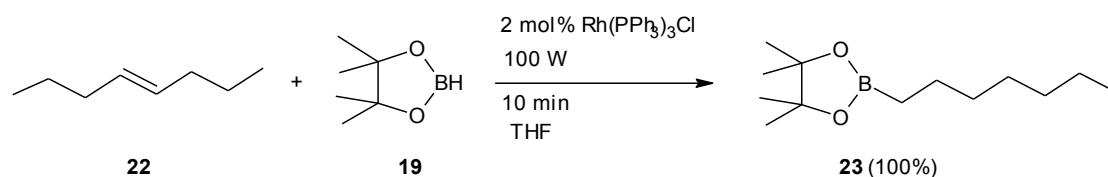
Three years after the report by Westcott *et al.*,<sup>13</sup> Pereira and Srebnik reported a new and more stable hydroborating agent, pinacolborane (**19**). This hydroborating agent was found by Pereira and Srebnik to hydroborate terminal olefins (**20**) in the presence

of  $\text{Rh}(\text{PPh}_3)_3\text{Cl}$  to furnish the desired products in good to excellent yields without any trace of the disproportionation product is being observed (**Scheme 7**).<sup>14,15</sup>



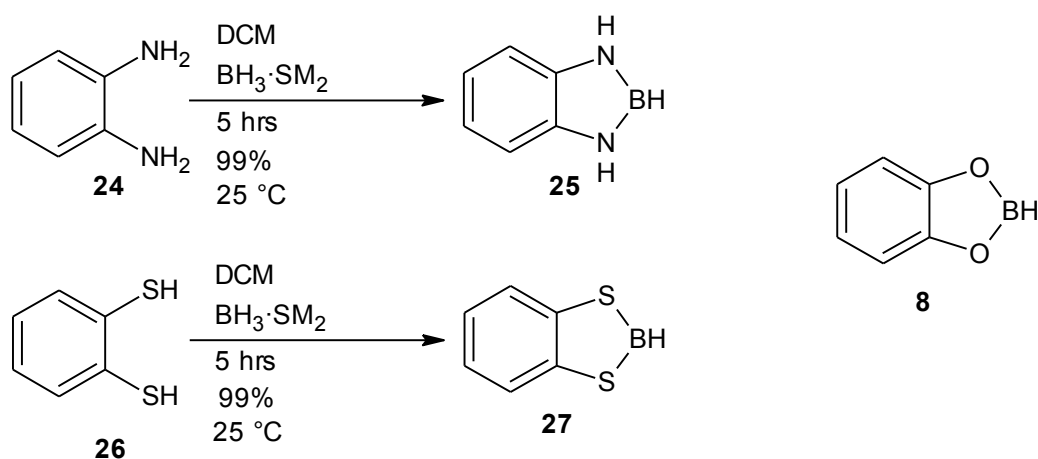
**Scheme 7**

The chemistry of  $\text{Rh}(\text{PPh}_3)_3\text{Cl}$  catalysed hydroboration reactions of olefins with pinacolborane opened a new area of research in organic chemistry. In 2006, Hadebe and Robinson reported the hydroboration of internal trans-4-octene (**22**) with pinacolborane (**19**) in the presence of  $\text{Rh}(\text{PPh}_3)_3\text{Cl}$ , a reaction which has been reported, by several authors, to be unsuccessful.<sup>16,17</sup> According to Hadebe and Robinson,<sup>18</sup> the hydroboration of trans-4-octene with pinacolborane under the influence of microwave irradiation furnished the isomerised product (**23**) in 100% yield (**Scheme 8**).



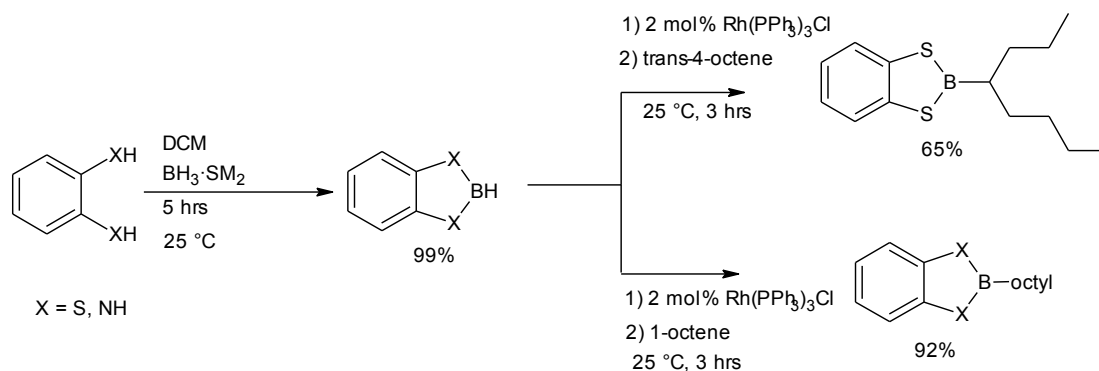
**Scheme 8**

In search of a new, stable and moisture insensitive hydroborating agents which are also less prone to disproportionation compared to catecholborane, Hadebe and Robinson extended their hydroboration studies to include the possibility of using heterosubstituted sulphur and nitrogen analogues of catecholborane as potential hydroborating agents.<sup>19</sup> During their studies, the authors reported that the reaction of borane solution with either 1,2-diaminobenzene (**24**) or 1,2-dithiabenzene (**25**) furnished the desired heterosubstituted borane species in yields greater than 99% (**Scheme 9**).



**Scheme 9**

Based on the authors experimental findings, the nitrogen (**25**) and the sulphur (**27**) analogues are more stable than the oxygenated analogue (**8**). To investigate the suitability of these newly formed reagents in the hydroboration realm, Hadebe reacted both species with internal and terminal olefins in the presence of 2 mol%  $\text{Rh}(\text{PPh}_3)_3\text{Cl}$ . Hadebe's results showed that these compounds are not only stable towards disproportionation but they are also excellent hydroborating agents furnishing the expected boronate esters in yields of up to 92% (**Scheme 10**).



**Scheme 10**

In addition of being significantly easy to handle and highly reactive towards olefins, these species have been shown to be regioselective, as they place the boron atom at the terminal carbon of the double bond relative to catecholborane.<sup>19</sup> In keeping with this, Geier *et al.* have recently (2009) described the remarkable directing effects of the amide group on the regioselective hydroboration of olefins with pinacolborane. Geier *et al.* disclosed that the hydroboration of amide-containing olefins regioselectively place

the boron atom at the terminal position.<sup>20</sup> Their findings were supported by Tackacs and co-workers<sup>21</sup> and Smith *et al.*<sup>22</sup> who also described the role of sulphide moiety in directing the placement of the boron atom across the double bond.

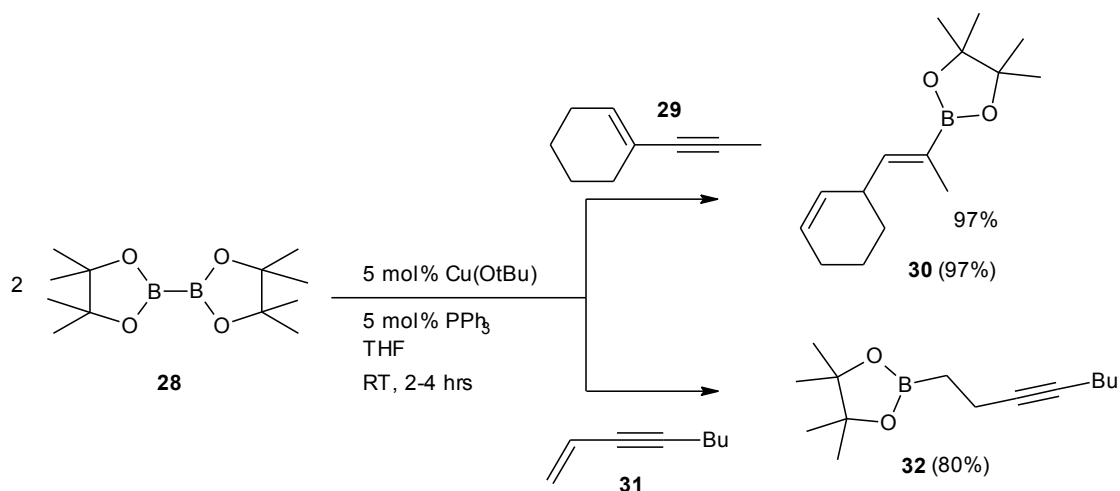
In a related study Lata *et al.* have reported that the addition of a Lewis acid such as trispentafluoroboron as co-catalyst in the Rh(PPh<sub>3</sub>)<sub>3</sub>Cl catalysed hydroboration of aromatic olefins with pinacolborane significantly reduces the reaction time and improve the regioselectivity of this reaction.<sup>23</sup> With respect to Lata *et al.*, the Rh(PPh<sub>3</sub>)<sub>3</sub>Cl catalysed hydroboration of aromatic olefins with pinacolborane results in a 50:50 mixture of internal and terminal hydroborated products, however, the addition of a small amount of trispentafluoroboron leads to exclusive formation of the terminal hydroborated product. The reason as to why this reagent improves the regioselectivity of this reaction is not clear as reported by Lata *et al.*<sup>23</sup>

The research focus on the subject of metal-catalysed hydroboration has changed and the scope of this reaction has expanded dramatically over the last two years. While extensive research has previously been concentrated at the development of rhodium<sup>24</sup>,<sup>25</sup> and iridium<sup>26</sup> as transition metal catalysts for the hydroboration reaction, little effort has been directed at expanding the scope of transition metal to rare-earth and main-group metals that could promote and improve the efficiency of this methodology.<sup>27</sup>

Current efforts have, however, been devoted at exploring the capabilities of other transition, rare-earth and main group metals as catalysts for the hydroboration reactions. As a consequence, a range of metals have, more recently, been reported to catalyse this reaction including copper,<sup>28</sup> zinc,<sup>29</sup> calcium,<sup>30</sup> magnesium,<sup>31</sup> iron,<sup>32</sup> gold,<sup>33</sup> nickel<sup>34</sup> and molybdenum.<sup>35</sup> Among the above mentioned metals, a great deal of attention has been directed to copper. This metal has been reported to have the outstanding catalytic activity in the hydroboration realm.<sup>36</sup>

In 2011 Sasaki *et al.*,<sup>37</sup> have described an efficient and high yielding regioselective monohydroboration of conjugated alkenes and alkynes under the influence of copper(I) catalyst. The monohydroboration of alkenes and alkynes have previously been reported to be a challenging and a low rewarding process.<sup>38</sup> However, according to Sasaki *et al.*<sup>37</sup> this process furnishes in excellent yield the desire monohydroborated product in less than 4 hours. For example, the hydroboration of 1,3-enyne (**31**) in the presence of 5 mol% of Cu(OtBu) and PPh<sub>3</sub> in THF gave 3-alkyborate (**2**) in 80%

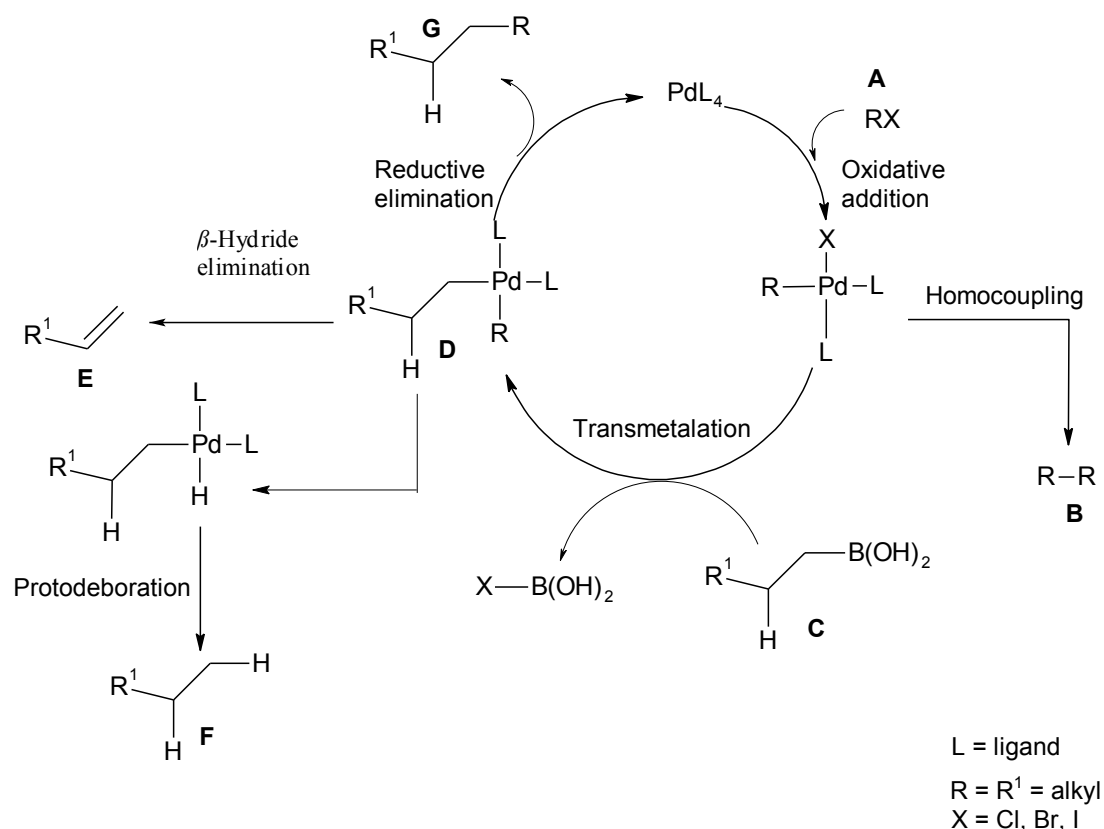
isolated yields, while the hydroboration of (**29**) provided the desired product in 97% yield (Scheme 2.13). In addition, the products obtained *via* this method were demonstrated to be suitable coupling partners in the Suzuki-Miyaura cross-coupling reactions.<sup>37</sup>



Scheme 11

## 2.3 Suzuki-Miyaura Cross-Coupling Reactions of Organometallic Reagents possessing a $\beta$ -Hydrogen(s).

Palladium-catalysed cross-coupling reaction between organic electrophiles such as alkyl halides or triflates with organometallic reagents such as organoborane compounds in the presence of a base has emerged as one of the most versatile, efficient and powerful methodology in organic synthesis.<sup>39</sup> This reaction broadly known as the Suzuki-Miyaura cross-coupling reaction has been known for its efficient carbon-carbon bonds construction capability which make possible the formation of complex molecules from simple precursors.<sup>40</sup> Historically, the Suzuki-Miyaura cross-coupling reaction of non-activated organoborane compounds (which possess a  $\beta$ -hydrogen) with any organic electrophiles (aryl, alkenyl, alkyl halides or triflates) has presented severe drawbacks due to several factors including: (i) sluggish oxidative addition of the organometallic reagent to the Pd-metal centre of the catalyst,<sup>41</sup> (ii) degradation of these species during the coupling process *via*  $\beta$ -hydride elimination and (iii) slow reductive elimination of the coupled-product which usually leads to proto-demetalation side products (**Figure 8**).<sup>42</sup>



**Figure 8: Catalytic cycle of Suzuki-Miyaura Cross-Coupling reaction.**

As illustrated in scheme 2.14, the oxidative addition of alkyhalide **A** to the palladium centre is a sluggish process leading to homocoupling side product **B**.<sup>43</sup> The transmetalation of organometallic boron compound transfers the organic group from the boron to the metal centre giving intermediate **D**.<sup>44</sup> Similar to the oxidative addition step; slow reductive elimination leads to the formation of side product **E** via  $\beta$ -hydride elimination, which in turn facilitate the formation of the protodeborated side-product **F**. Successful reductive elimination of intermediate **D** couples the two organic moieties providing the desired product **G** in poor yields. From scheme 2.14 it is clear that the cross-coupling of organometallic reagents which possess a  $\beta$ -hydrogen with organic electrophiles is a great challenge for chemists as it reveals a number of possible routes which lead to the formation of undesirable products.<sup>45, 46</sup>

These shortcomings have hindered the development of non-activated organoborane compounds (which possess a  $\beta$ -hydrogen) as coupling partners in the Suzuki-Miyaura cross-coupling reactions.<sup>47</sup> Consequently, very little progress has previously been achieved in the  $\text{C}(sp^3)\text{-C}(sp^3)$  cross-coupling between non-activated organoborane

and organic electrophiles when compared to the activated organoborane counterparts (which will be discussed in details in chapter four).<sup>48</sup>

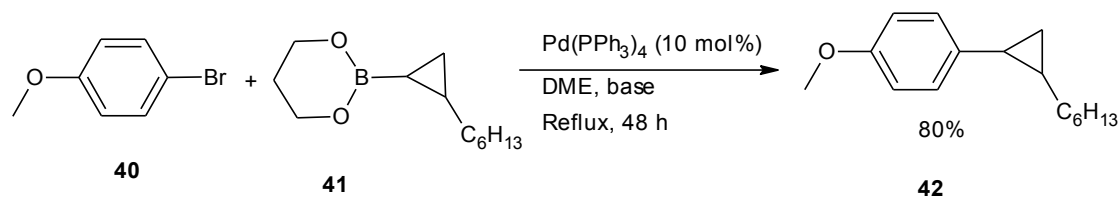
The growing importance of  $C(sp^3)-C(sp^3)$  bond construction in the synthesis of natural products and biologically active compounds has called for the establishment of reaction conditions that will effectively facilitate the cross-coupling process between  $C(sp^3)$ -organometals and electrophiles (especially those with  $\beta$ -hydrogen).<sup>7</sup> consequently, numerous research groups have in the last decade concentrated their focus towards exploring the combination of different ligands (with electron donating and electron-withdrawing groups), bases, transition metal catalysts and solvents with the aim of finding efficient, mild and high yielding reaction conditions for the construction of  $C(sp^3)-C(sp^3)$  bonds.<sup>49</sup>

In the following sections, attention will be focused on the progress that has been achieved in the development of this methodology. These sections are divided according to the type of organometallic boron derivatives used as coupling partners including (i) boronic acids and their ester, (ii) organoboranes and finally (iii) the use of alkyltrifluoroborate reagents.

### 2.3.1 Suzuki Coupling with Boronic acid and their esters

In 1989, Suzuki and co-worker<sup>50</sup> reported the cross-coupling reaction of alkylboronic esters with a range of aryl halides in the presence of  $PdCl_2(dppf)$  or  $Pd(PPh_3)_4$  as catalysts. According to Suzuki, this reaction afforded moderate to good yields when strong and highly toxic thallium hydroxide or thallium carbonate bases were used.<sup>50</sup> Despite the high yields obtained, the use of thallium bases presented a serious drawback for the application of this protocol.

In search of more efficient and milder reaction condition, Marsden and Hildebrand<sup>51</sup> reported, in 1996 that the cross-coupling reaction of a cyclopropylboronate with aryl bromides in the presence of potassium tertiary butoxide (*t*-BuOK) as a base and of  $Pd(PPh_3)_4$  as catalyst proceeded smoothly furnishing the desired coupled products in high yields (Scheme 2.15)<sup>51</sup>



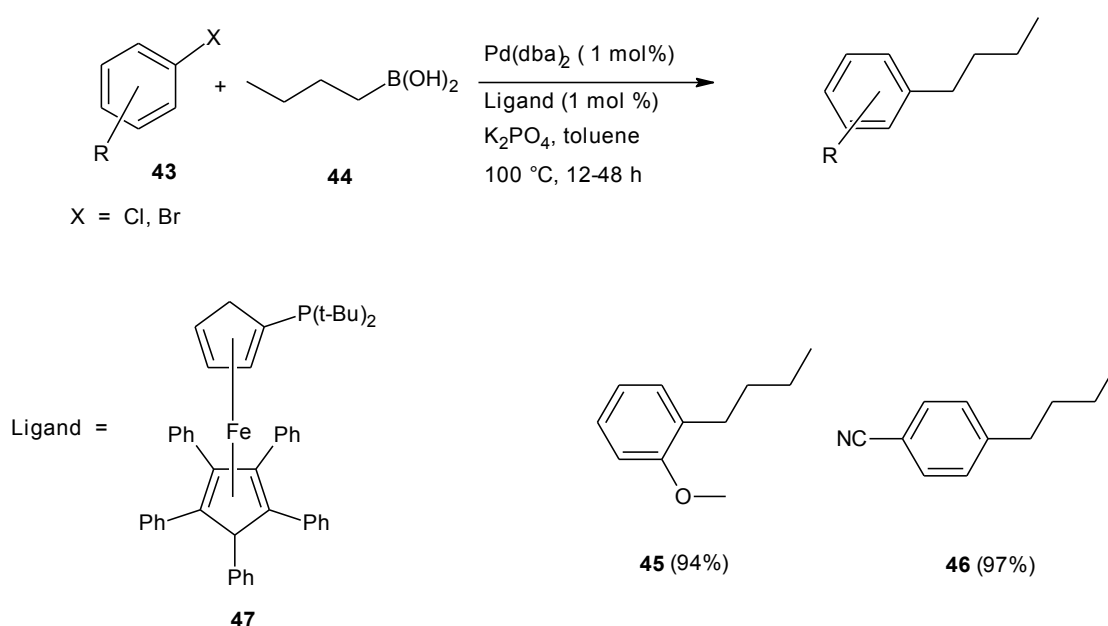
**Scheme 12**

A year later, Charette *et al.*<sup>52</sup> reported that the cross coupling between cyclopropylboronate and iodocyclopropane derivatives afforded the expected coupled products in excellent yields under the reaction conditions reported by Marsden and Hildebrand.<sup>52</sup>

In 2001, de Meijere and Lohr<sup>53</sup> also confirmed the efficiency of the reaction condition initially reported by Marsden and Hildebrand; however, their results also revealed that this protocol is not suitable for the cross-coupling of electron-deficient electrophiles such as *p*-bromonitrobenzene and methyl-2-iodobenzoate as no cross-coupling products were observed when these electrophiles were used.<sup>53</sup> According to the authors, the failure of this reaction was attributed to slow oxidative addition of *p*-bromonitrobenzene and methyl-2-iodobenzoate to the metal centre which leads to undesirable products (see Scheme 2.14 for more details).

In search for better reaction conditions that will allow the cross-coupling reaction of electron-deficient electrophiles, Hartwig *et al.*<sup>54</sup> reported an efficient ferrocenyl dialkylphosphine ligand which when coupled with  $\text{Pd(dba)}_2$  catalyst the cross-coupling reaction between *n*-butylboronic acid and various aryl bromides and chlorides (Scheme 2.16). Hartwig *et al.*<sup>54</sup> reported that a 1:1 stoichiometric ratio of a ligand and  $\text{Pd(dba)}_2$  in the presence of  $\text{K}_3\text{PO}_4$  as a base, furnished the expected products in excellent yields. In addition of being highly efficient, this protocol was also reported to be insensitive to steric hindrance of the electrophiles whilst also compatible with both electron-withdrawing and electron-donating functionalities (Scheme 2.16).<sup>54</sup>

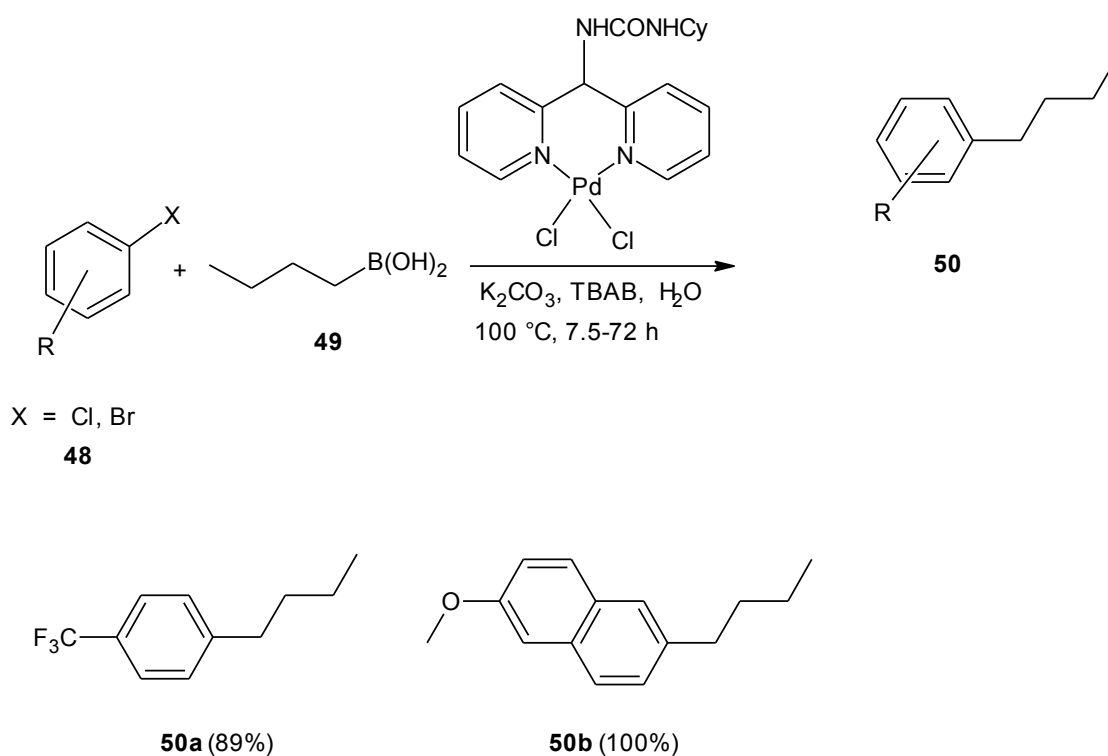




**Scheme 13**

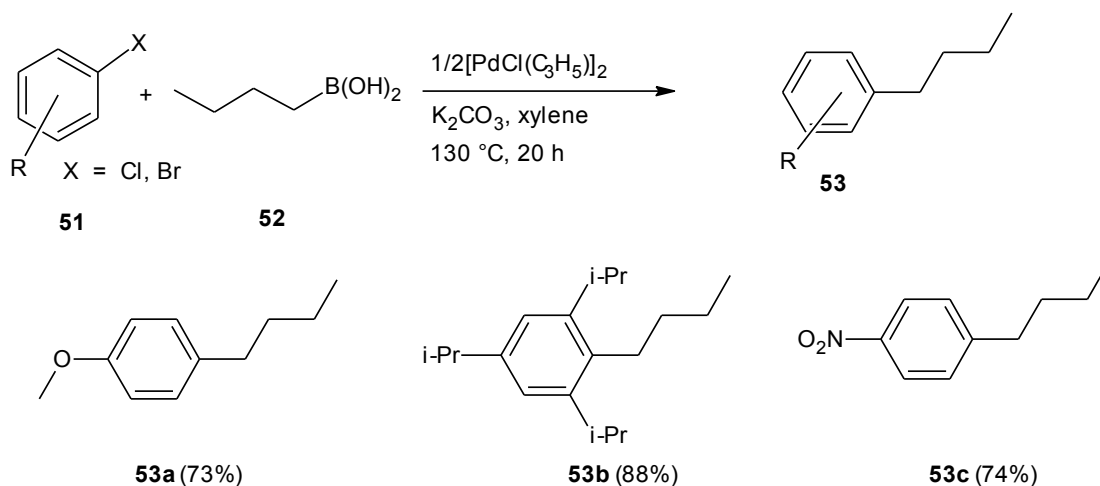
According to Hartwig *et al.* the addition of an electron-rich ferrocenyl dialkylphosphine ligand (**47**) accelerates the oxidative addition of electron-rich and electron-deficient electrophiles, by suppressing the formation of undesirable products such as homo-coupled and  $\beta$ -hydride elimination.<sup>54</sup>

Having realised the impact of modifying the ligand on the overall efficiency of the Suzuki cross-coupling reaction, Najere and co-workers<sup>55</sup> reported the use of a water soluble di-(2-pyridyl)-methylamine-palladium catalyst for the Suzuki-Miyaura cross-coupling reaction. With this catalyst, aryl halides bearing both electron-withdrawing and /or electron-donating groups could couple smoothly to trimethylboroxine and *n*-butylboronic acid in the presence of K<sub>2</sub>CO<sub>3</sub> as a base and Bu<sub>4</sub>NBr as an additive in refluxing water (**Scheme 14**).<sup>55</sup> According to the authors, the pyridyl-based ligands provide the palladium centre with sufficient electrons density such that it facilitates the oxidation addition of aryl halides to the metal centre.



**Scheme 14**

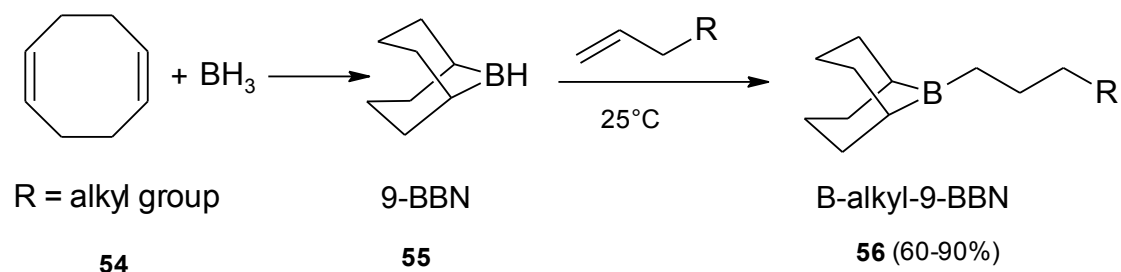
Kondolff and others<sup>56</sup> developed  $[\text{PdCl}(\text{C}_3\text{H}_5)]_2/\text{cis,cis,cis-1,2,3,4-tetrakis(diphenylphosphinomethyl)cyclopentane}$  (tedcyp) as catalyst for the Suzuki cross-coupling between alkyboronic acid with sterically demanding 2,4,6-triisopropyl-bromobenzene and electron-deficient *p*-nitrobenzene.<sup>56</sup> The efficiency of tedcyp as catalyst was confirmed four years later by Kondolff and others when he reported a successful coupling of *n*-butylboronic acid with various aryl halides (Scheme 15).<sup>57</sup>



**Scheme 15**

### 2.3.2 Suzuki Coupling with Alkyl boranes

The chemistry of alkylborane compounds was discovered in the early 1950s by Brown and Subba<sup>2</sup> when they were investigating the scope and limitations of the hydroboration reactions. Extensive studies by the authors revealed that the hydroboration of sterically hindered olefins such as 1.5-cyclooctadiene (**54**) yielded the corresponding borane 9-borabicyclo[3.3.1]nonane (9-BBN) (**55**) in excellent yields.<sup>58</sup> This reagent was shown to hydroborate olefins regioselectively at the least hindered carbon of the double bond furnishing the desired alkylboranes (**56**) in reasonable yields (**Scheme 16**).<sup>59</sup>

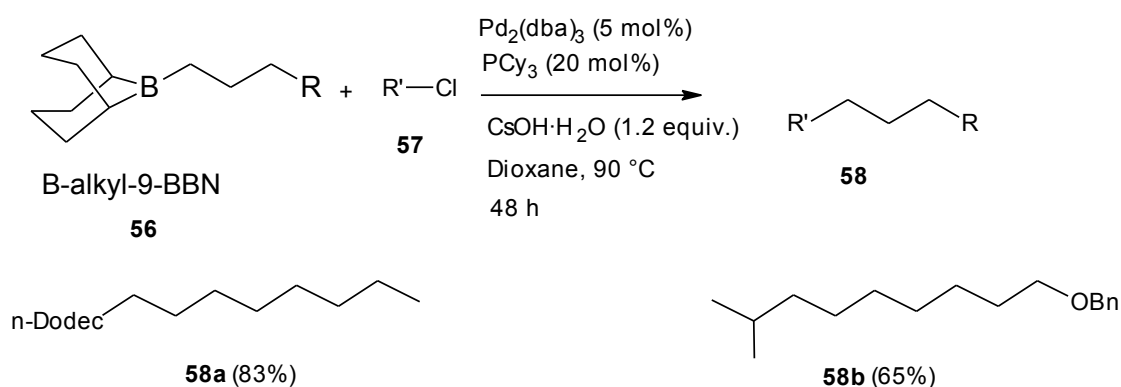


**Scheme 16**

The application of the resulting B-alkyl-9-BBN in the Suzuki cross-coupling methodology was, however, limited due to air and moisture sensitivity of these

species and also due to the lack of well developed catalysts and ligands that could promote the utility of B-alkyl-9-BBN as a potential Suzuki coupling partner.<sup>7</sup> With the recent developments in the Suzuki cross-coupling reactions between non-activated organoboranes with either activated or non-activated electrophiles, a lot of progress has been achieved in the cross-coupling reaction involving B-alkyl-9-BBN as a coupling partner.<sup>60</sup>

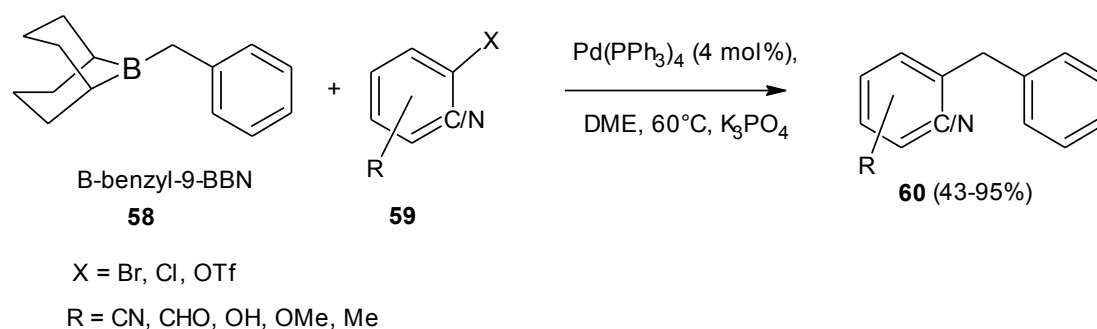
In 2001, Fu *et al.*<sup>61</sup> disclosed a successful alkyl-alkyl cross-coupling reaction between B-alkyl-9-BBN and iodoalkenes in the presence of a 1:2 stoichiometric ratio of Pd(OAc)<sub>2</sub>/PCy<sub>3</sub> as a catalyst complex. Of significance is the fact that this reaction furnished the desired coupled products at room temperature.<sup>61</sup> Building on the foundation laid by Fu *et al.*, Kirchoff *et al.*<sup>62</sup> accomplished the cross-coupling between B-alkyl-9-BBN and less reactive alkyl chlorides in the presence of a catalytic amount of Pd<sub>2</sub>(dba)<sub>3</sub>/PCy<sub>3</sub> in dioxane (**Scheme 17**).<sup>62</sup>



**Scheme 17**

The Capretta group<sup>63</sup> were previously interested in improving and extending the scope of the alkyl-alkyl Suzuki-Miyaura cross-coupling to tosylates as electrophiles, as a consequence, the group synthesised a range of phosphine-based ligands and investigated them in the coupling reactions. During the screening process, they found a suitable Pd/ligand combination (**Scheme 18**) which furnished the alkyl-alkyl Suzuki-Miyaura coupled-products in excellent yields in the presence of tosylates as electrophiles.<sup>63</sup> A year later, Flaherty and co-workers<sup>64</sup> disclosed the synthesis of methylene-linked biaryls from *B*-benzyl-9-BBN and a range of aryl/heteroaryl halides

and triflates. In this case,  $\text{Pd}(\text{PPh}_3)_4$  and  $\text{K}_3\text{PO}_4$  were found to be the appropriate additives for the coupling reaction (**Scheme 18**).<sup>64</sup>

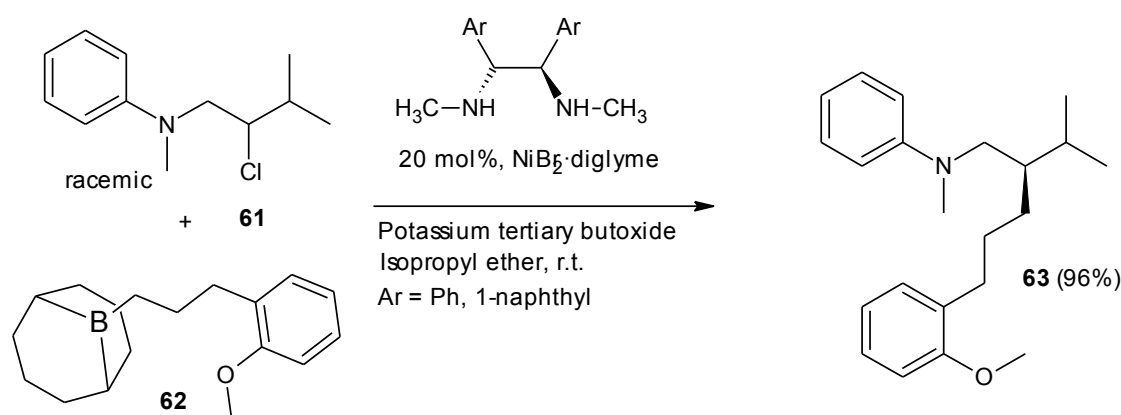


**Scheme 18**

In 2008, Velente *et al.* were the first to report the use of an ionic carbene-based ligand in the alkyl-alkyl Suzuki cross-coupling reactions. According to the authors, the treatment of alkyl bromides with B-alkyl-9-BBN in the presence of  $\text{Pd}(\text{dba})_2$  and a carbene ligand provided the coupled-products in moderate yields. In 2010, the same group reported a modified procedure which uses a non-ionic carbene ligand.<sup>65</sup> In this case, the cross-coupling between B-alkyl-9-BBN with alkyl bromides afforded the desired products in excellent yields compared with their early observation using an ionic carbene ligand. However, no clarity was afforded by the authors as to why the non-ionic carbene ligands afforded greater yields when compared to ionic carbene ligand.<sup>65</sup>

In order to extend the scope of metal catalysts used in the alkyl-alkyl Suzuki cross-coupling methodology, Fu and Le<sup>66</sup> have recently discovered the use of nickel (II) as catalyst that facilitates the alkyl-alkyl Suzuki cross-coupling of unactivated secondary halides, including more challenging chloride electrophiles, with B-alkyl-9-BBN.<sup>66</sup>

The group further reported an improved procedure which uses a stereoconvergent amine ligand. Fu and Le reported that the ligand serves to control the stereochemistry of the newly formed carbon-carbon bonds. This provided for the first time an efficient procedure for an enantioselective alkyl-alkyl Suzuki cross-coupling of unactivated secondary halides with B-alkyl-9-BBN under the influence of nickel catalysts (**Scheme 19**).<sup>67</sup>



**Scheme 19**

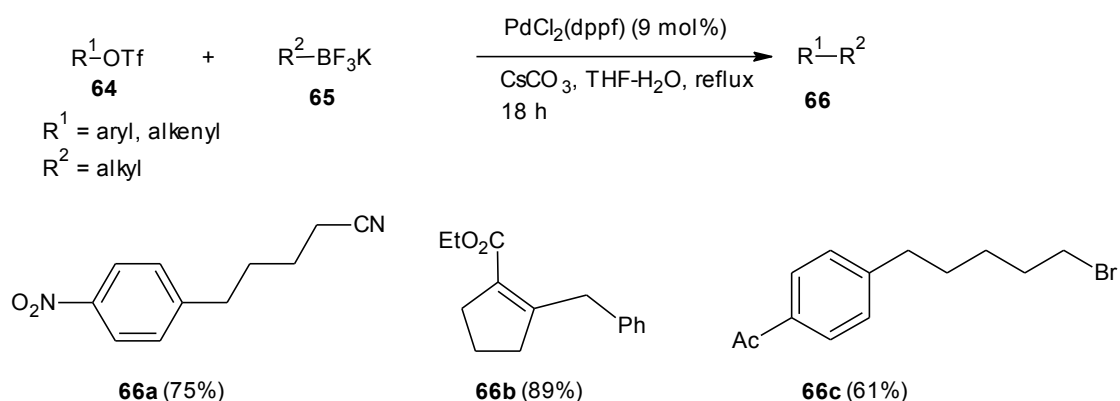
In a related study Taylor *et al.*<sup>68</sup> demonstrated the efficiency of stereo-controlled nickel catalysed alkyl-alkyl cross-coupling reaction to provide the expected product in moderate to good yields.<sup>68</sup>

### 2.3.3 Suzuki Coupling with Alkyltrifluoroborates

Alkyltrifluoroborates present another class of interesting compounds encountered in the alkyl-alkyl Suzuki cross-coupling reactions.<sup>69</sup> These compounds have found applications in the Suzuki cross-coupling methodology due to their high stability, which is comparable to that of boronic acid, and their ready availability from the reaction of  $\text{KHF}_2$  and a range of organoboranes.<sup>69</sup> The application of these compounds as the Suzuki coupling partners has found its stand only recently due to the significant effort of Molander's group in popularising the application and the versatility of these compounds in the alkyl-alkyl cross-coupling reactions.<sup>70</sup>

Molander and co-workers<sup>70</sup> reported the cross-coupling of potassium alkyltrifluoroborate with a range of aryl and alkenyl triflates in the presence of  $\text{Pd}(\text{dppf}^1)\text{Cl}_2 \cdot \text{CH}_2\text{Cl}_2$  and  $\text{CsCO}_3$  as a catalyst and base, respectively. Under these reaction conditions, the desired coupled-products were obtained in good to moderate yields (**Scheme 20**).<sup>70</sup>

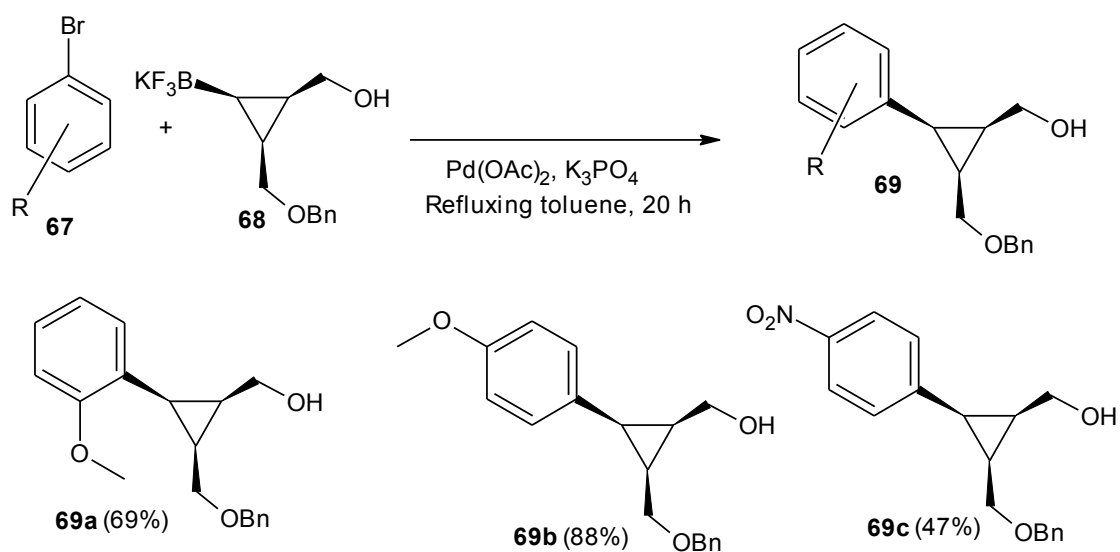
<sup>1</sup> Diphenylphosphinoferrocene



**Scheme 20**

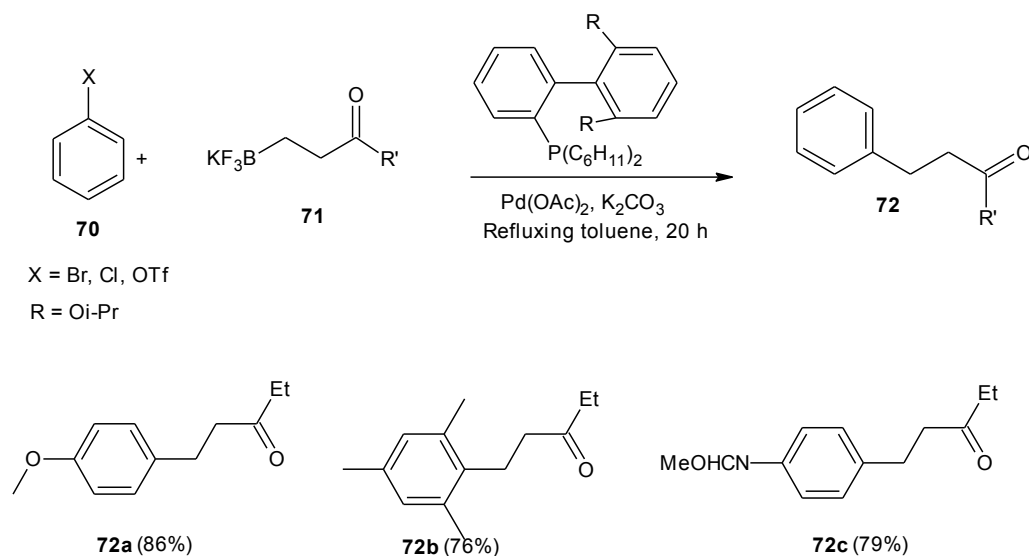
Extensive studies conducted by the same group soon revealed that although various aryl triflates were smoothly coupled under these reaction conditions, aryl triflates bearing electron-donating functionalities were did not undergo the expected transformation under the same reaction conditions.<sup>70</sup> To overcome these drawbacks, Molander and *et al.* attempted to accelerate the coupling reaction by conducting the reaction at elevated temperatures. However, this modification ultimately led to the formation of side products *via* protio-delahogeneration and proto-deboration processes which are rarely observed in this protocol.<sup>71</sup>

In search for the reaction conditions that will be suitable for the cross coupling of electron rich triflates, the Charette group<sup>72</sup> reported that the cross coupling of a more stable cyclopropyltrifluoroborate (**64**) with electron-rich electrophiles (**65**) such as 2- and 4-methoxy-bromobenzene in the presence of diphenylphosphine-based ligand went smoothly in refluxing toluene affording the desired coupled-products in modest to good yields.<sup>72</sup>



**Scheme 21**

The successful coupling of electron-rich triflates was attributed to the presence of diphenylphosphine-based ligand which facilitates the oxidative addition of the electrophiles to the metal centre thus suppressing the formation undesirable products as reported by the group. Soon after this report, Molander *et al.*<sup>73</sup> reported that the carbonyl-functionalised potassium trifluoroborate were smoothly coupled with arylhalides and triflates under the influence of a bulky phosphine-based ligand and an easily accessible  $\text{Pd}(\text{OAc})_2$  catalyst (**Scheme 22**).<sup>73</sup>



**Scheme 22**



In a related study, Nie and co-workers<sup>74</sup> have described the synthesis of polypyridyl compounds from the Suzuki-Miyaura cross-coupling reactions. In this case, potassium vinyltrifluoroborate underwent a smooth coupling with bromopolypyridine in the presence of a cheap and easily accessible triphenylphosphine ligand.<sup>74</sup> This protocol provided the expected products in excellent yields of up to 93% in aqueous solution using Pd(OAc)<sub>2</sub> and Cs<sub>2</sub>CO<sub>3</sub> as the catalyst and a base, respectively.

Although many effective Suzuki coupling partners such as alkylborane, alkylboronic acids, alkylbornates esters, and potassium trialkyl fluoroborate have successfully been employed in the Suzuki cross-coupling context, the full potential of these reagents have not yet been fully reached mainly because of a number of limitations associated with each coupling partner including: The incompatibility of alkylborane with a vast number of functionalities and their short shelf life significantly limit the applicability of these reagents in the cross couplings.<sup>59</sup> The air and moisture sensitivity of these species demands precautionary handling thus making their application limited only to small-scale production.

Alkylboronic acid and their esters can also readily undergo the Suzuki transformation with numerous electrophiles,<sup>56</sup> however, the cross-coupling reactions of these species are accompanied by the high rate of protodeboration and  $\beta$ -hydride elimination routes which, in turn, demands the addition of three fold excess of boronic acid for better conversion. In addition, toxic thallium bases such as TlOH and Tl<sub>2</sub>CO<sub>3</sub> or stronger bases such as *sec*-butyllithium, which are also moisture sensitive, are required to achieve the desired products in moderate yields.<sup>75</sup>

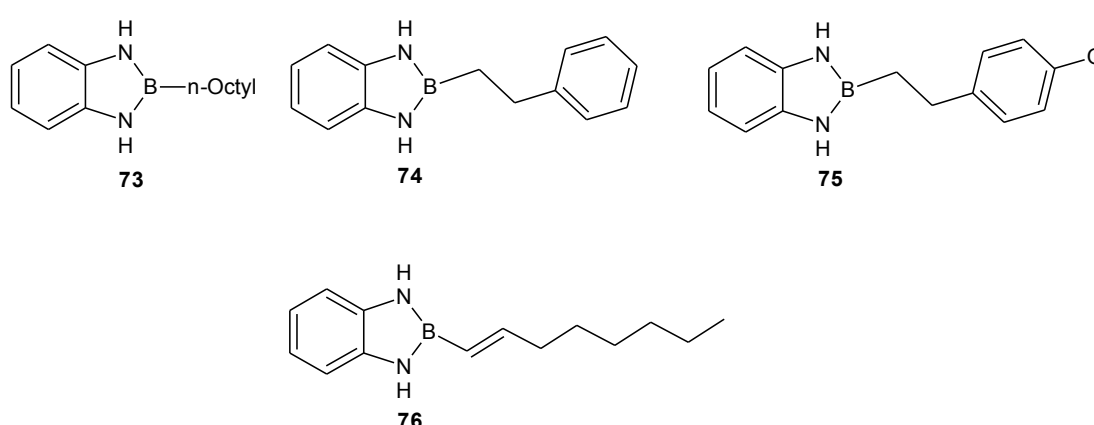
Although tremendous effort has, recently been devoted at the development of potassium trialkylborates as potential and promising Suzuki coupling partners, the chemistry of these compounds has not been fully developed as yet. Throughout the past, considerable effort, in the Suzuki cross-coupling area has been concentrated largely on the development of suitable metal/ligand combinations which facilitate the formation of the desired products. To date, progress has been achieved through these efforts; however, very little effort has been directed on improving the Suzuki cross-coupling reaction through expanding the scope of organoboron derivatives that could be used as coupling partners. Specifically, the use of nitrogen-based organoboron in

the cross couplings has, to the best of our knowledge, never been described in the Suzuki cross-coupling realm.

## 2.4 Aims of Chapter two

The main aims of this project are:

- To conduct synthetic studies of 2-alkylbenzo-1,3,2-diazaborolane compounds such as 2-octylbenzo-1,3,2-diazaborolane (**73**), 2-phenethylbenzo-1,3,2-diazaborolane (**74**) and 2-{2-(4-methoxyphenyl)-ethyl}benzo-1,3,2-diazaborolane (**75**) from the reaction of benzo-1,3,2-diazaborolane with the corresponding terminal olefins in the presence of a catalytic amount of Wilkinson's catalyst (Figure 2.3); and,
- To synthesise 2-(1*E*-1-hexenyl)-benzo-1,3,2-benzodiazaborolane (**76**) from the cyclocondensation of 1*E*-hexenylboronic acid and 1,2-diaminobenzene (**Figure 9**); and,
- To assess the potential application and the efficiency of these compounds as the Suzuki-miyaura cross-coupling partners by reacting them with a range of aryl halides bearing both electron-donating and withdrawing functional groups.



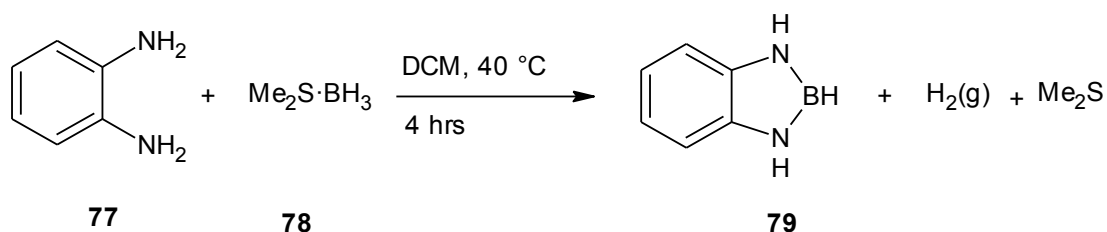
**Figure 9: 2-(Alkyl/alkenyl/aryl)benzo-1,3,2-diazaborolane compounds**

## 2.5 Results and Discussion

### 2.5.1 Synthesis of 2-alkylbenzo-1,3,2-diazaborole

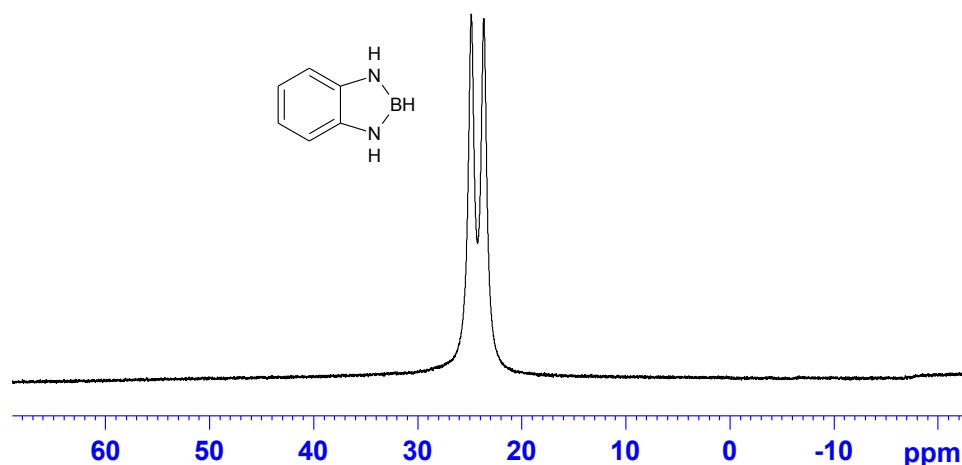
#### 2.5.1.1 Synthesis of 2-benzo-1,3,2-diazaborolane (79)

Hadebe and Robinson <sup>19</sup> previously reported the synthesis of 2-benzo-1,3,2-diazaborolane from the reaction of dimethylsulfide borane complex ( $\text{Me}_2\text{S}\cdot\text{BH}_3$ ) with 1,2-diaminobenzene (**77**). According to the author, the dropwise addition of  $\text{Me}_2\text{S}\cdot\text{BH}_3$  (**78**) solution to a dichloromethane solution of 1,2-diaminobenzene (**77**), at 40 °C afforded the desired compound in more than 99% yield. Following the protocol documented by the author, 2-benzo-1,3,2-diazaborolane (**79**) was successfully synthesised and was obtained as colourless oily product in yields greater than 99% (NMR) (**Scheme 23**).<sup>19</sup>



**Scheme 23**

The successful synthesis of 2-benzo-1,3,2-diazaborolane was confirmed with  $^{11}\text{B}$  NMR spectroscopy which showed a doublet at 23.9 ppm indicating that the boron atom is attached only to one active hydride atom (**Figure 10**).

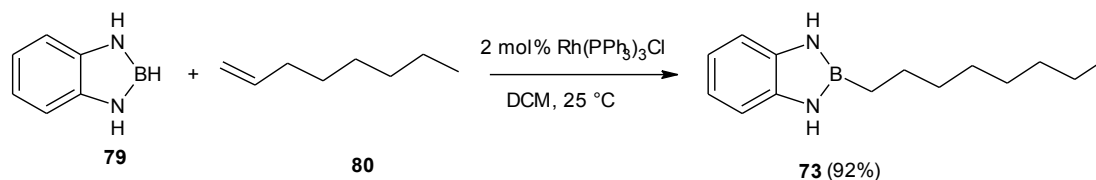


**Figure 10:**  $^{11}\text{B}$  NMR spectrum of 2-benzo-1,3,2-diazaborole (**79**)

In a comparative study conducted by Hadebe and Robinson, the authors reported that 2-benzo-1,3,2-diazaborolane is significantly less prone to decomposition due to better  $\pi$ -electron overlap between the vacant  $2p_z$ -orbitals on the boron atom and the two chelating nitrogen atoms when compared to the corresponding oxygen analogous (catecholborane). These electrons are thought to be back-donated from the two nitrogens to the boron atom which in turn reduces the electrophilicity of the boron atom making it less susceptible to nucleophilic attack. Encouraged by the remarkable stability of 2-benzo-1,3,2-diazaborolane relative to that of catecholborane, Hadebe and Robinson investigated the suitability of 2-benzo-1,3,2-diazaborolane as a hydroborating agent in rhodium-catalysed hydroboration reactions.<sup>19</sup>

### 2.5.1.2 Synthesis of 2-octylbenzo-1,3,2-diazaborole (**73**)

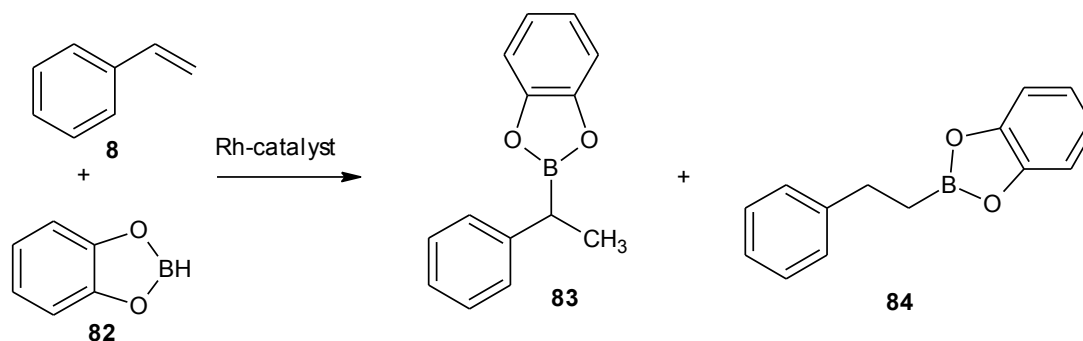
Hadebe and Robinson<sup>19</sup> previously reported that the reaction of 2-benzo-1,3,2-diazaborolane **A** with 1-octene (in the presence of 2 mol%  $\text{Rh}(\text{PPh}_3)_3\text{Cl}$ ) furnished the desired coupled-product (**73**) in 92% yield as an orange-yellow wax.<sup>19</sup>



**Scheme 24**

It is well reported in the literature that the rhodium-catalysed hydroboration reactions of terminal olefins with catecholborane (HBcat) or pinacolborane (HBpin) leads to

the formation of both the internal and the terminal hydroborated-products.<sup>76</sup> For instance, the hydroboration of styrene with catecholborane (**8**) leads to a mixture of branched (**83**) and non-branched catecholboronate esters (**84**) (Scheme 25).<sup>10,18</sup>

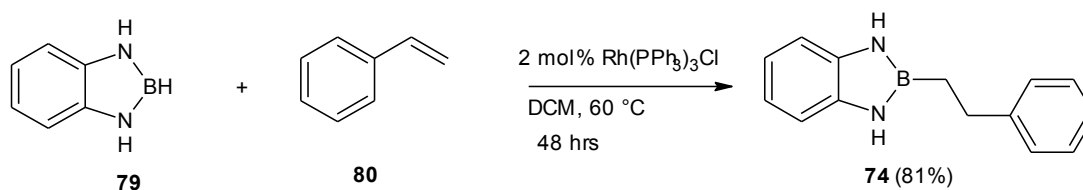


**Scheme 25**

In contrast to catecholborane, 2-benzo-1,3,2-diazaborolane has been reported to hydroborate terminal olefins regioselectively placing the boron atom at the least hindered carbon atom of the double bond, however, the author did not provide the explanation for the remarkable regioselectivity exhibited by 2-benzo-1,3,2-diazaborolane.<sup>19</sup>

### 2.5.1.3 Synthesis of 2-Phenethylbenzo-1,3,2-diazaborolane (**74**)

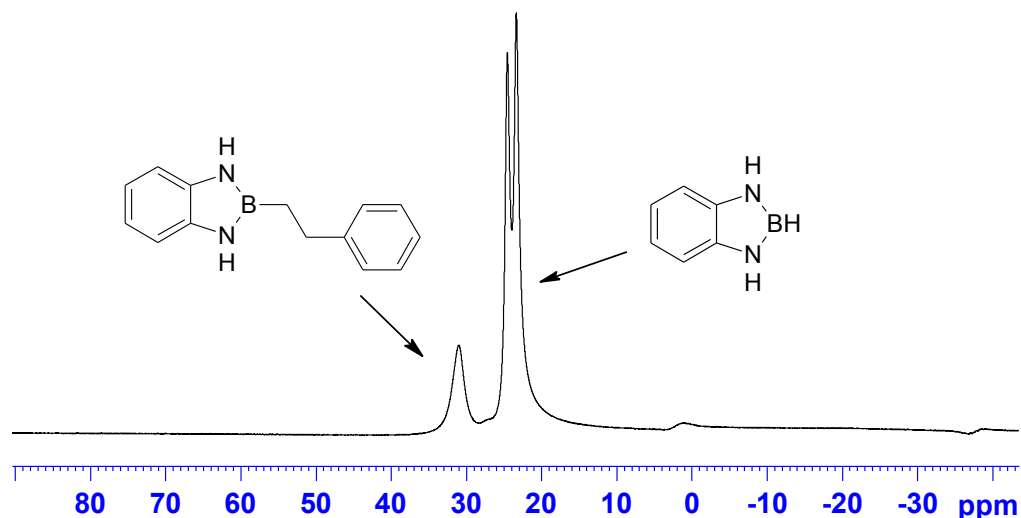
Following the procedure reported in the literature,<sup>19</sup> a freshly prepared DCM solution of 2-benzo-1,3,2-diazaborole (**79**) was heated at ca. 60 °C in the presence of 1.5 fold excess styrene (**82**) and a catalytic amount of Wilkinson's catalyst.



**Scheme 25**

After one hour of heating, a small aliquot was withdrawn from the reaction mixture and subsequently analysed using the  $^{11}\text{B}$  NMR spectroscopy. The spectrum obtained revealed a doublet at 23.9 ppm and a new singlet resonating at 31.2 ppm, which were

assigned to the starting material (**79**) and the desired coupled-product (**74**), respectively (**Figure 11**).



**Figure 11:**  $^{11}\text{B}$  NMR spectrum of compounds **74** and **79**

The presence of the doublet on the spectrum clearly corresponding to starting material had necessitated further heating at  $60^\circ\text{C}$  for 48 hrs. The  $^{11}\text{B}$  NMR spectroscopic analysis of the reaction mixture, after 48 hrs of heating, showed only a singlet resonating at  $\delta 31.2$  ppm confirming complete conversion of the starting material to the desired-coupled product (**Figure 12**).

The title compound was obtained, after purification through flash column chromatography, as a cream-white amorphous powder in 81% yield. The  $^1\text{H}$  and  $^{13}\text{C}$  NMR spectra of the product were acquired in deuterated chloroform, and were consistent with the anticipated structure. The HRMS analysis showed a molecular peak resonating at 221.1247 mass units which is in excellent agreement with the calculated molar mass for  $\text{C}_{14}\text{H}_{14}\text{N}_2\text{B}$  of  $221.1250 \text{ g mol}^{-1}$ . The infrared spectrum showed the absorption bands at  $3385$  and  $3364 \text{ cm}^{-1}$  which are assigned to the unsymmetrical stretching of the N–H bonds.

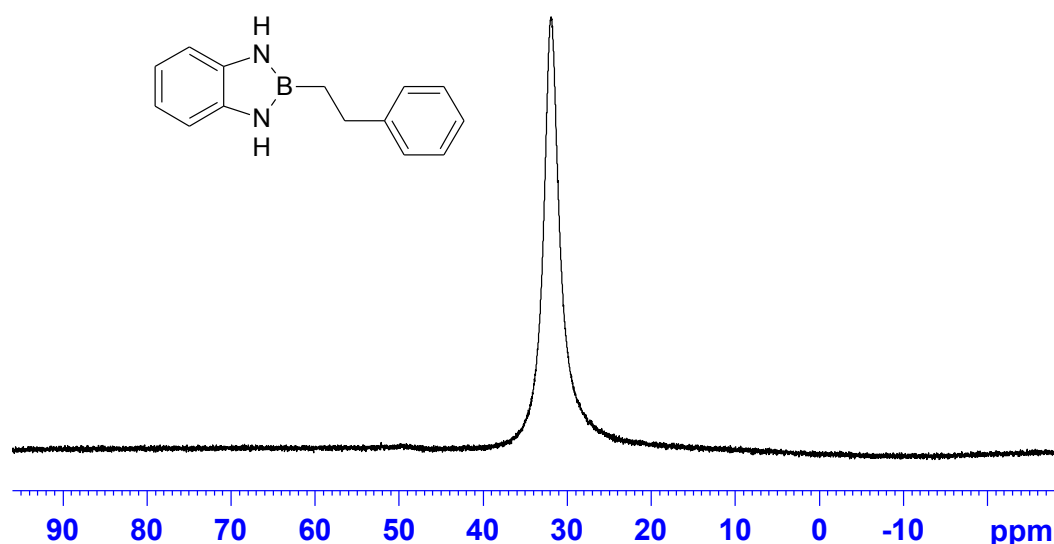
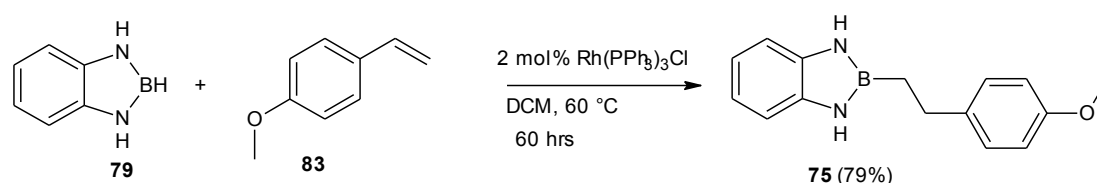


Figure 12:  $^{11}\text{B}$  NMR spectrum of compound 74

#### 2.5.1.4 Synthesis of 2-[2-(4-methoxyphenyl)-ethyl]-benzo-1,3,2-diazaborolane (75)

To further confirm that the rhodium-catalysed hydroboration of terminal olefins with 2-benzo-1,3,2-diazaborolane leads, exclusively, to the formation of the terminal hydroborated product, 4-methoxystyrene was reacted with 2-benzo-1,3,2-diazaborolane in the presence of 2 mol% Wilkinson catalyst. According to the authors, a freshly prepared DCM solution of 2-benzo-1,3,2-diazaborolanes hydroborated 4-methoxystyrene (**81**) cleanly at 60 °C providing only the desired terminal-hydroborated diazaborolane product (**75**) as a cream white powder in 78% isolated yields (Scheme 26).<sup>77</sup>

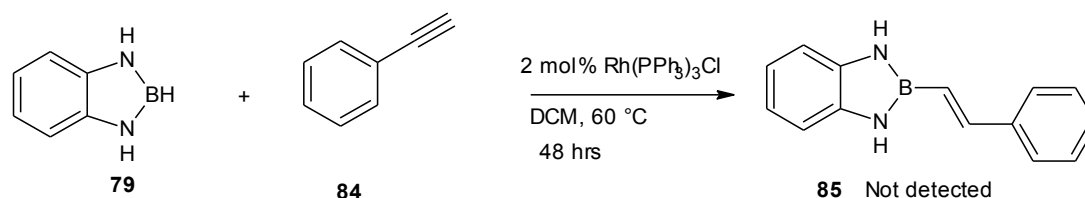


Scheme 26

The  $^1\text{H}$  and  $^{13}\text{C}$  NMR spectra of the obtained cream white powder was consistent with the expected structure showing the correct number of carbon signals and the integral ratios corresponding to the expected number of protons. The HRMS of the product showed a molecular peak  $[\text{M}^+]$  with a  $m/z$  of 251.1360 mass units which is in good agreement with the calculated molecular mass for  $\text{C}_{15}\text{H}_{17}\text{BN}_2\text{O}$  of 251.1356  $\text{g mol}^{-1}$ .<sup>77</sup>

### 2.5.1.5 Attempted synthesis of 2-styrenyl-benzo-1,3,2-diazaborolane (85)

With the rhodium-catalysed hydroboration reaction conditions in hand, we extended our investigation to include terminal alkynes as the substrates.



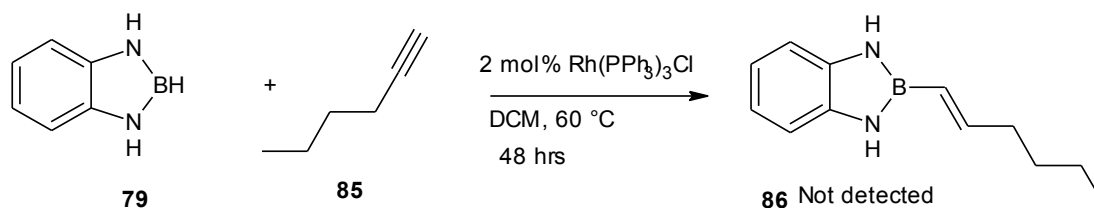
**Scheme 27**

In this case, phenylacetylene was reacted with 2-benzo-1,3,2-diazaborolane in the presence of Wilkinson's catalyst at 60 °C. Subsequent  $^{11}\text{B}$  NMR spectroscopic analysis of the reaction mixture revealed only a doublet which indicated the presence of only the starting material. Heating the reaction mixture for 60 hours, at the same temperature, did not give the desired product as the  $^{11}\text{B}$  NMR spectroscopic analysis of the reaction still revealed the doublet ascribable to the starting material. Attempts to circumvent these challenges by doubling the amount of the catalyst and increasing the temperature to 100 °C did not lead any improvement.

### 2.5.1.6 Synthesis of 2-(1*E*-1-hexenyl)-benzo-1,3,2diazaborolane (76)

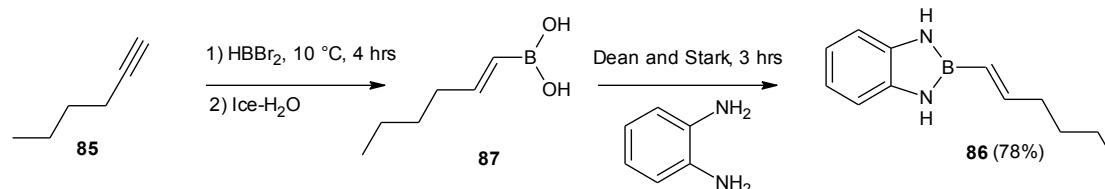
Following the failure of the hydroboration of phenylacetylene, we envisaged that the failure of the above mentioned reaction was attributed to the presence of the phenyl ring which hinders the coordination of phenylacetylene to the rhodium catalyst due to the shorter carbon-carbon triple bond (when compared to carbon-carbon double bond), which in turn, create steric hindrance around the rhodium centre. The reaction was repeated with 1-hexyne as a substrate. No coupled-product was obtained regardless of changing the nature of the substrate (**Scheme 28**).





**Scheme 28**

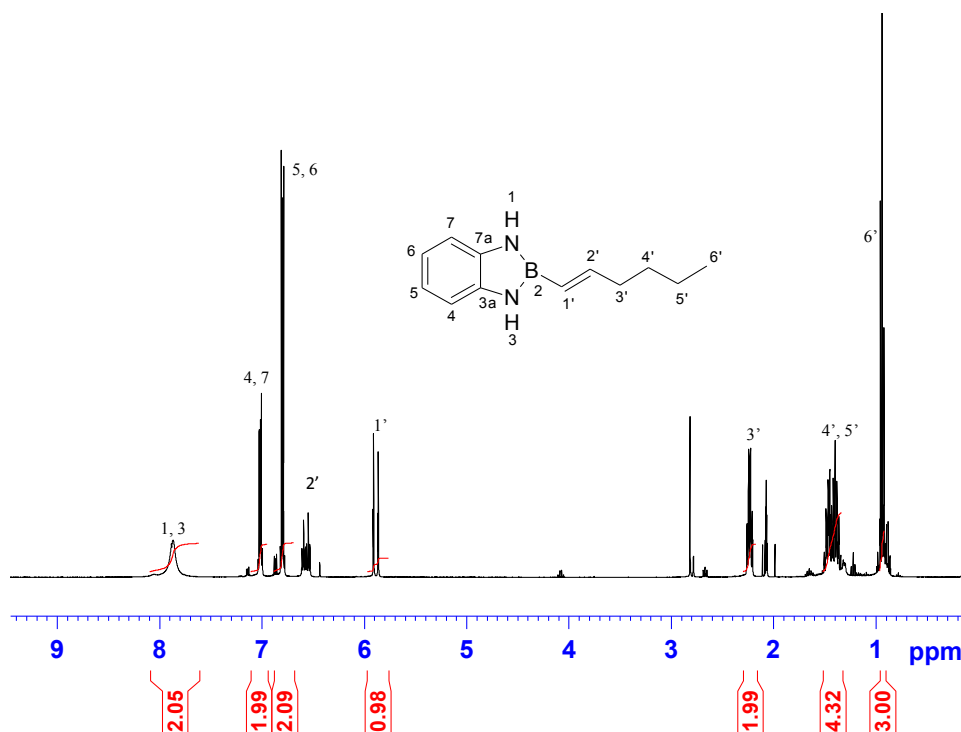
These observations clearly indicated that 2-benzo-1,3,2-diazaborolane (**79**) was not a suitable hydroborating agent for terminal alkynes under optimal reaction conditions. To overcome this challenge, another procedure for the hydroboration of terminal olefins, reported by Brown and Campbell,<sup>78</sup> was used for the preparation of the desired product. In this regard, a DCM solution of 1-hexyne was reacted with a solution of  $\text{HBBBr}_2 \cdot \text{Me}_2\text{S}$  at 10 °C under the atmosphere of dry nitrogen. To the resulting colourless solution, after the evaporation of the volatile components, was added ice-water and the precipitated boronic acid was collected through filtration. Without further purification, the collected boronic acid was heated under reflux in the presence of 1.5 equiv excess of 1,2-diaminobenzene under a Dean and Stark condition (**Scheme 29**).



**Scheme 29**

The desired *novel* product was obtained as white amorphous powder in 78% yield after column chromatography purification. The  $^1\text{H}$  NMR spectroscopic analysis of the purified product showed signals which are consistent with the assigned structure (**figure 2.6**). The spectrum shows the presence of triplet ( $J = 7.3$  Hz) at  $\delta$  0.98 ppm. Which integrates for three protons and is coupled to one of the protons (integrating for four protons) whose signal resonates in the region  $\delta$  1.33-1.52 ppm. The triplet corresponds to proton 6'-H and the multiplet resonating at  $\delta$  1.33-1.52 ppm was assigned to 4'-H and 5'-H. The two protons resonating at  $\delta$  2.19-2.27 ppm were also found to be coupled to the multiplet at  $\delta$  1.33-1.52 ppm and were assigned to 3'-H. A doublet of triplets ( $J = 18.1$  Hz) resonating at  $\delta$  5.88 ppm is coupled to protons 3' as

well as to a doublet of triplets ( $J = 18.3$  Hz) whose peak appears at 6.51 ppm. The doublet of triplets at  $\delta$  5.88 ppm and at  $\delta$  6.51 ppm were assigned to 2'-H and 1'-H, respectively (**Figure 13**).



**Figure 13:**  $^1\text{H}$  NMR spectroscopic analysis of compound 86

The structure of the product was also confirmed by HRMS which showed a molecular peak at  $m/z$  199.1404 which agrees well with the calculated  $m/z$  value for  $\text{C}_{12}\text{H}_{17}\text{BN}_2$  of (199.1407). The infrared spectrum showed the absorption bands at 3381, 3360 and  $1634\text{ cm}^{-1}$  are assigned to the unsymmetrical N–H and C–B bonds stretching frequencies, respectively.

### 2.5.2 The Suzuki-Miyaura Cross-Coupling Reaction between benzodiazaborolyl Derivatives with various Aryl Halides.

The importance of the carbon-carbon bond formation from the cross-coupling reaction between organoboron compounds possessing a  $\beta$ -hydride with organic electrophiles is well demonstrated by the substantial efforts devoted towards the development and the improvement of the methodology.<sup>43</sup> Tremendous progress has been made to-date including conducting the cross-coupling reaction at room temperature<sup>61</sup> and using previously non-reactive aryl chlorides and tosylates as electrophiles.<sup>79</sup>

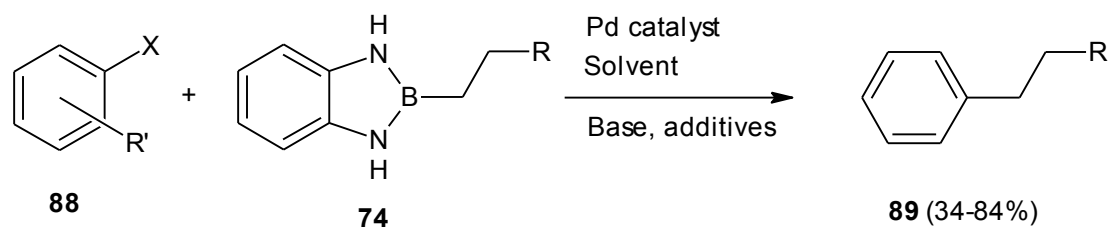
Despite these achievements the focus in this area has been concentrated on the development of new palladium catalysts and the use of complex ligands to accelerate the rate of the cross-coupling reaction. Since its discovery, the Suzuki cross-coupling reaction has been based on the utility of boronic acids and their esters as nucleophilic coupling partners. Little effort has been focused at improving this methodology by extending the scope of organoboron compounds that can be used in this coupling reaction.<sup>7</sup> Only recently researchers devoted their focus towards investigating the potential utility of other organoboron derivatives such as alkyltrifluoroborates as the coupling partners in the Suzuki cross-coupling reaction realm.<sup>80</sup>

despite their ease accessibility and higher stability compared to their oxygen counterparts nitrogen-based organoboron compounds have to the best of our knowledge, never been reported in the Suzuki-Miyaura cross-coupling reactions as the nucleophilic coupling partners.<sup>19</sup>

The enhance stability of the nitrogen-based organoboron compounds compared to the oxygen counterparts have to be attributed to the significant back-donation of electrons from the nitrogen atoms to the empty  $2p_z$ -orbital of the boron atom.<sup>19,81</sup> This effect enhances the charge density on the  $2p_z$ -orbital of the boron atom, which in turn, stabilises the nitrogen-based organoboron.<sup>19</sup> In a separate mechanistic study, Soderquist and Matos<sup>82</sup> have reported that a base coordinates to the boron atom and donates its electron to the empty  $2p_z$  orbital of the boron atom, this effect weakens the boron-carbon bonds which in turn facilitate the transmetalation of the organic group from the boron atom to the palladium centre. From this observation, it became clear that the higher the electron density on the boron atom the easier is the transmetalation step.

The higher electron density back-donated from the two chelating nitrogen atoms to the vacant  $2p_z$  orbital of the boron atom presumably enhances the nucleophilicity of the nitrogen-based organoboron compounds. This effect is expected to weaken the carbon-boron bond thereby accelerating the transmetalation step. This prompted us to investigate the application of nitrogen-based organoboron compounds in Suzuki-Miyaura cross-coupling reactions.

Herein, we outline the scope and limitations of the Suzuki cross-coupling reaction between the synthesised benzodiazaborolane compounds with aryl halides (**Scheme 30**).



X = Cl, Br, I

R' = NO<sub>2</sub>, COCH<sub>3</sub>, COOCH<sub>3</sub>

**Scheme 30**

In order to find the suitable reaction condition for the above cross-coupling reaction the reaction optimisation study was conducted. In this study, 2-octylbenzo-1,3,2-diazaborolane was reacted with bromobenzene as a substrate (Table 1). This reaction was repeated several times with an array of commonly used Suzuki coupling reagents (Table 1, entries 1-7). The use of a bulky Pd(PPh<sub>3</sub>)<sub>4</sub> in conjunction with either an aqueous or anhydrous K<sub>2</sub>CO<sub>3</sub> base afforded trace coupled products yields (0-2%) (Table 1, entries 2-4). The use of Pd(OAc)<sub>2</sub> and the addition of the supporting ligands failed to improve the efficiency of the coupling reactions (Table 1, entries 5-7). Further investigation with 2-octylbenzo-1,3,2-diazaborolane incorporating the use of K<sub>3</sub>PO<sub>4</sub>·H<sub>2</sub>O, PCy<sub>3</sub>, Pd(OAc)<sub>2</sub> in conjunction with the microwave irradiation afforded a slightly higher yield of 50% in 2 hrs (Table 1, entry 9) compared to conventional heating which furnished the coupled-product in only 30% yield (Table 1, entry 8). The yield improved dramatically to 88% when solvent free reaction conditions were employed under the microwave irradiation and the reaction reached completion within 5 minutes (Table 1, entry 10).

**Table 1. Pd-mediated cross-coupling reaction between 2-octylbenzo-1,3,2-diazaborolane with bromobenzene, optimal reaction conditions survey.**

Entry	Catalyst	Base	Ligand	Conditions	Yields (%)
1	Pd(PPh <sub>3</sub> ) <sub>4</sub>	aq Na <sub>2</sub> CO <sub>3</sub>	none	A	0
2	Pd(PPh <sub>3</sub> ) <sub>4</sub>	aq K <sub>2</sub> CO <sub>3</sub>	none	A	0
3	Pd(PPh <sub>3</sub> ) <sub>4</sub>	K <sub>2</sub> CO <sub>3</sub>	none	A <sup>a</sup>	2
4	Pd(PPh <sub>3</sub> ) <sub>4</sub>	K <sub>2</sub> CO <sub>3</sub>	none	B	2
5	Pd(OAc) <sub>2</sub>	K <sub>2</sub> CO <sub>3</sub>	PPh <sub>3</sub>	A <sup>a</sup>	5
6	Pd(OAc) <sub>2</sub>	K <sub>2</sub> CO <sub>3</sub>	PPh <sub>3</sub>	B	2
7	Pd(OAc) <sub>2</sub>	K <sub>3</sub> PO <sub>4</sub> ·H <sub>2</sub> O	PCy <sub>3</sub>	A <sup>a</sup>	0
8	Pd(OAc) <sub>2</sub>	K <sub>3</sub> PO <sub>4</sub> ·H <sub>2</sub> O	PCy <sub>3</sub>	A <sup>b</sup>	30
9	Pd(OAc) <sub>2</sub>	K <sub>3</sub> PO <sub>4</sub> ·H <sub>2</sub> O	PCy <sub>3</sub>	B <sup>c</sup>	50
10	Pd(OAc) <sub>2</sub>	K <sub>3</sub> PO <sub>4</sub> ·H <sub>2</sub> O	PCy <sub>3</sub>	C	88

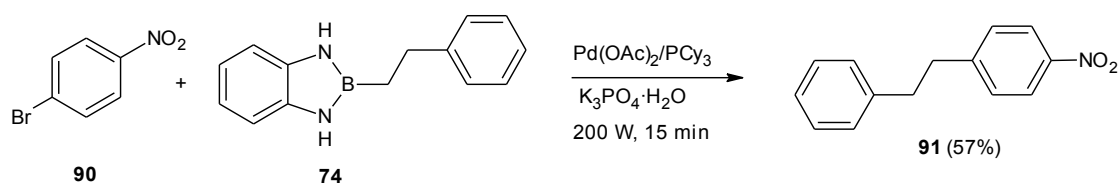
Reaction Conditions: (A) 1.0 equiv. of each reactant, 3.0 equiv. of base, 4 mol% catalyst, 8 mol% PCy<sub>3</sub> benzene, reflux for 24 hrs. (B) Same as A but DMF was used and the mixture was irradiated with 100W of microwave energy for 1 hr. (C) Same as A but no solvent was used and 8 mol% PCy<sub>3</sub> was added, reaction irradiated with 50W in 5 minutes. <sup>a</sup> DMF used. <sup>b</sup> 48 hrs reflux in THF. <sup>c</sup> 2hrs reflux in THF.

With optimal reaction conditions in hand, a range of aryl halides bearing either electron-donating, electron-neutral or electron-withdrawing substituents were coupled with benzodiazaborolyl derivatives under the Suzuki-Miyaura cross-coupling reaction conditions. In the following section, the synthesis of the Suzuki cross-coupled products from aryl halides and benzodiazaborolyl compounds will be discussed.

### 2.5.2.1 Synthesis of 1-(nitrophenyl)-2-phenylenethane (91)

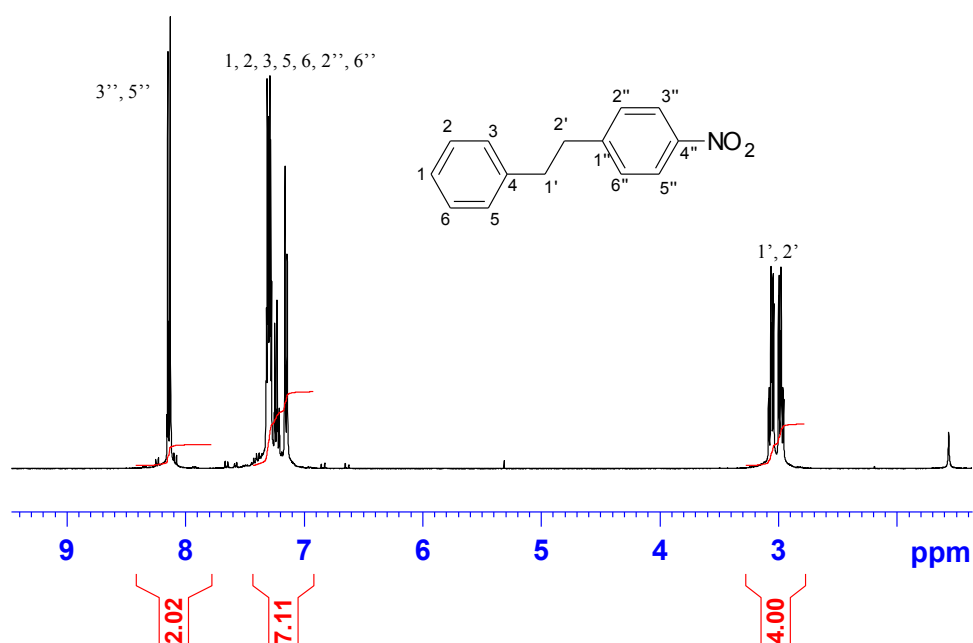
2-Phenethylbenzo-1,3,2-diazaborole was reacted with 4-bromonitrobenzene in the presence of 0.020 mmol of Pd(OAc)<sub>2</sub>, 0.039 mmol PCy<sub>3</sub> and 1.47 mmol K<sub>3</sub>PO<sub>4</sub>·H<sub>2</sub>O in toluene under microwave irradiation. After 15 minutes of microwave irradiation, the resulting black reaction mixture was filtered and the volatile components evaporated. The purification of the resulting residue, through silica gel column

chromatography, afforded the title compound as colourless crystals in 57% yield (**Scheme 31**).

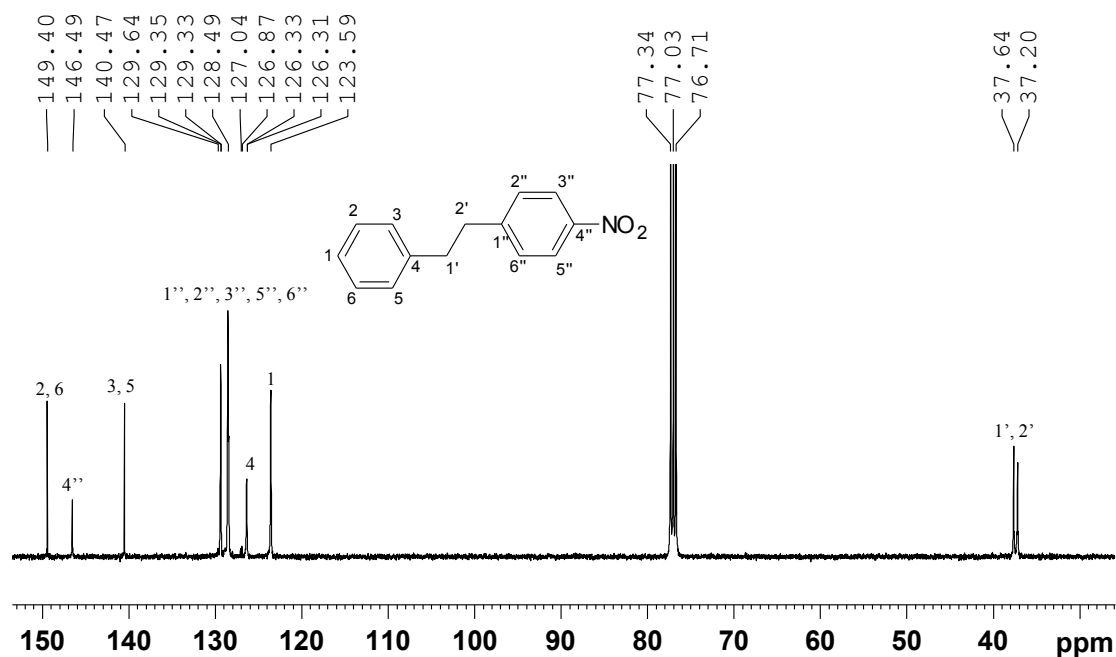


**Scheme 31**

The  $^1\text{H}$  spectrum of the product revealed the presence of two triplets resonating at  $\delta$  2.98 ppm and  $\delta$  3.06 ppm which corresponds to 1'-H and 2'-H, respectively. The doublet resonating at  $\delta$  7.15 ppm ( $J = 7.6$  Hz) is coupled to another doublet whose signal appears at  $\delta$  8.14 ppm ( $J = 8.16$  Hz). These doublets correspond to 2''-H, 6''-H, 5''-H and 3''-H, respectively. The multiplet resonating in the region  $\delta$  7.27-7.33 ppm was due to aromatic protons.



**Figure 15:  $^1\text{H}$  NMR spectrum of compound 91**

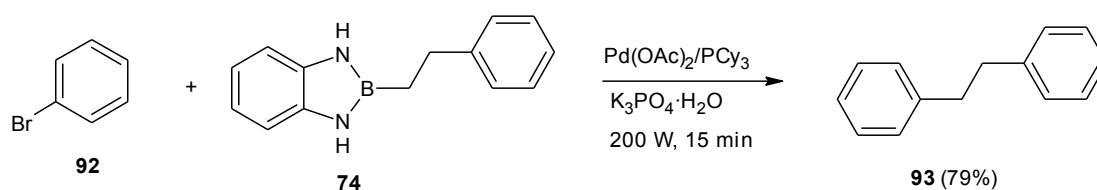


**Figure 15:** <sup>13</sup>C NMR spectrum of compound 91

The HRMS of the product showed a molecular peak  $[M^+ + Na^+]$  at  $m/z$  250.0847 which is in good agreement with the calculated  $m/z$  for C<sub>14</sub>H<sub>13</sub>NaO<sub>2</sub> 250.0844

### 2.5.2.2 Synthesis of 1,1'-Dibenzyl (93)

Following the general procedure used for the synthesis of 1-(4-nitrophenyl)-2-phenylethane (93), bromobenzene (92) was successfully coupled with 2-phenethylbenzo-1,3,2-diazaborole (74) furnishing the desired coupled-product in 79% yields, after purification through silica gel column chromatography (Scheme 32).



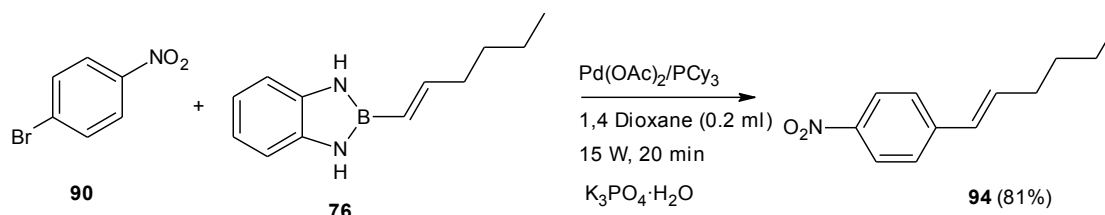
**Scheme 32**

The desired product was obtained as colourless crystals with a melting point in the range of 51 °C compares favourably with literature melting point of 50-51°C.<sup>83</sup> The <sup>1</sup>H and <sup>13</sup>C NMR spectral data of the title compound is consistent with the data reported in the literature.<sup>84, 85</sup>

## 2.5.3 Representative Procedure for the Suzuki Cross-Coupling Reaction using 2-(1*E*-hexenyl)-benzo-1,3,2-diazaborole.

### 2.5.3.1 Synthesis of 4-(1*E*-hexenyl) nitrobenzene (94)

2-(1*E*-hexenyl)-benzo-1,3,2-diazaborole (**76**) was efficiently coupled with 4-bromonitrobenzene (**90**) under the above mentioned conditions. The desired product was obtained as clear-yellow oil in 81% yield after the purification by chromatography (**Scheme 33**).



**Scheme 33**

. The <sup>1</sup>H and <sup>13</sup>C NMR spectra of the product revealed signals which are consistent with the assigned structure. The HRMS of the prepared product revealed a molecular ion peak [M<sup>+</sup> + Na<sup>+</sup>] at *m/z* 228.0999 mass units which is very close to the calculated *m/z* value for C<sub>14</sub>H<sub>18</sub>ONa of 228.1000



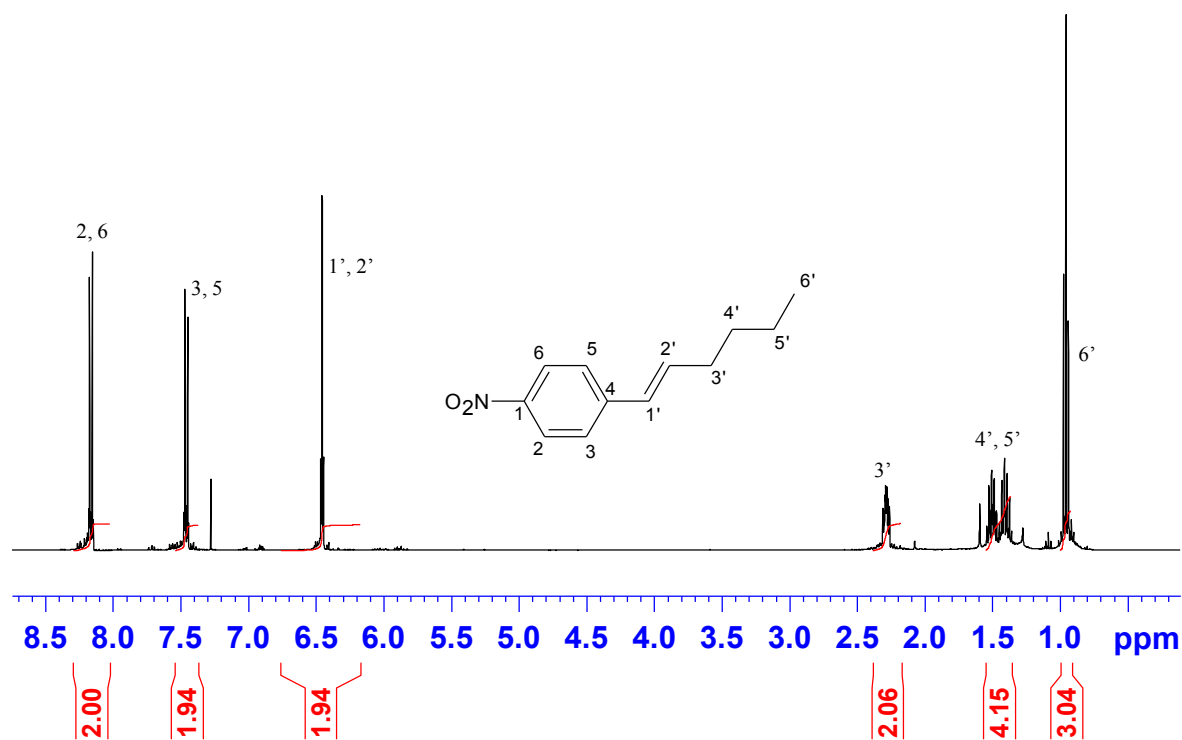


Figure 16. <sup>1</sup>H NMR spectrum of compound 94

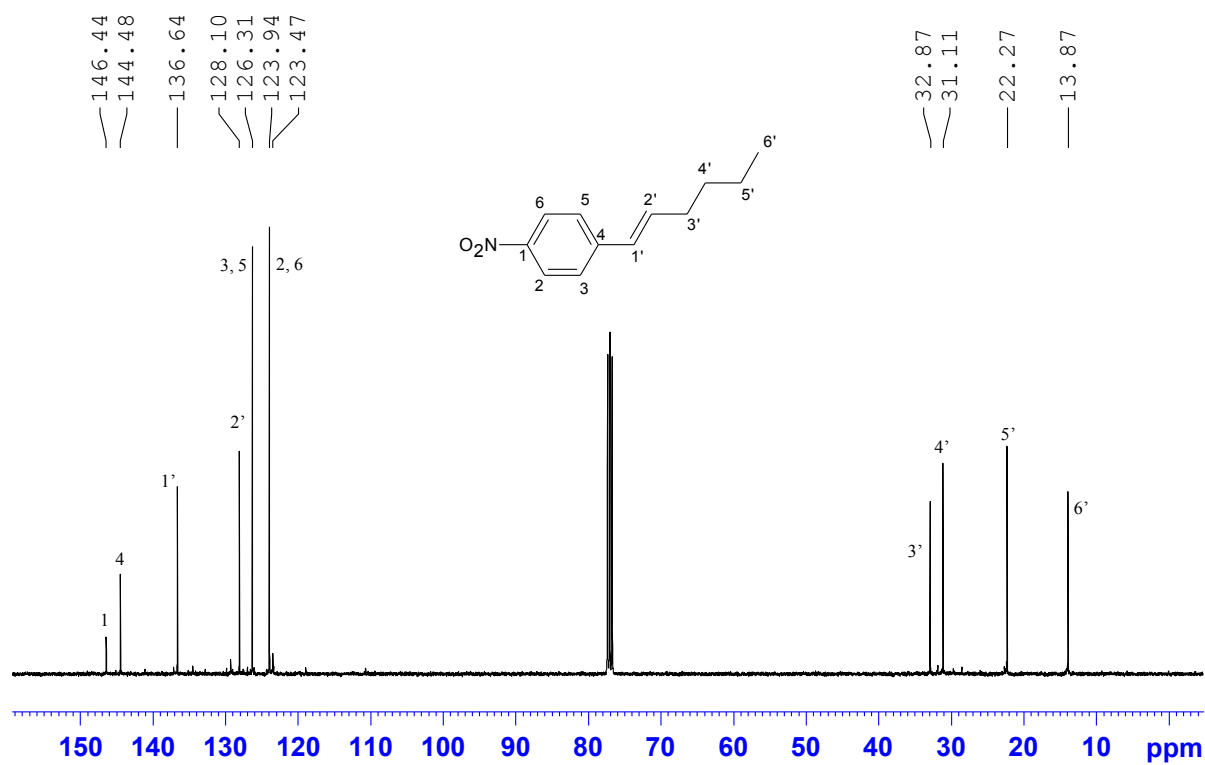
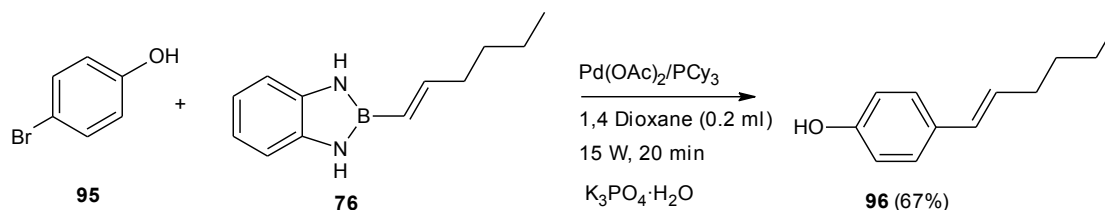


Figure 17: <sup>13</sup>C NMR spectrum of compound 94

### 2.5.3.2 Synthesis of 4-(1*E*-hexenyl)-phenol (**96**)

The title compound was prepared in 67% yield as a colourless oil from the reaction of 4-bromophenol (**95**) with 2-(1*E*-hexenyl)-benzo-1,3,2-diazaborole (**76**) following the representative procedure (Scheme 34).



Scheme 34

The structure of the coupled-product was confirmed using <sup>1</sup>H and <sup>13</sup>C NMR spectroscopic techniques which showed the expected number of signals and the integration ratios consistent with the assigned structure. The HRMS of the product showed a molecular peak resonating at *m/z* 175.1125 which agrees well with the calculated *m/z* value for C<sub>12</sub>H<sub>15</sub>O of 175.1123 (Figure 18).

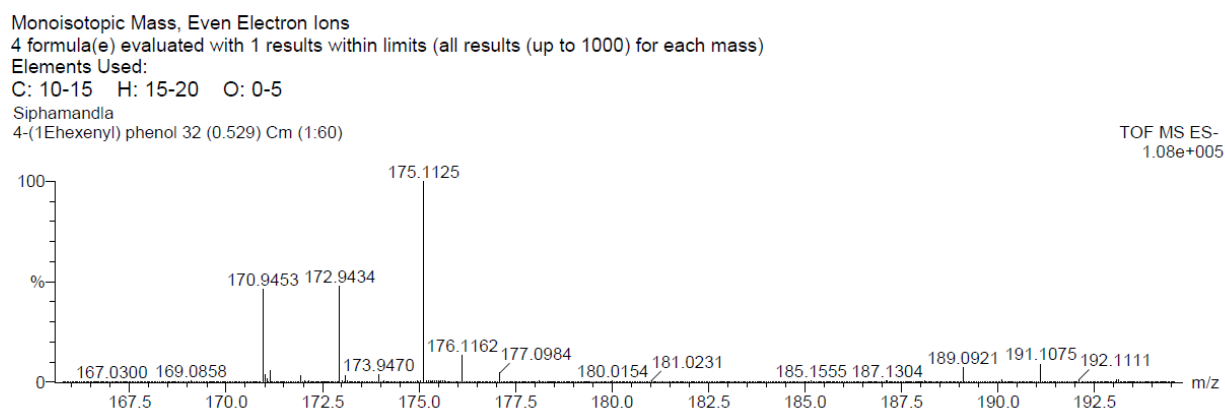
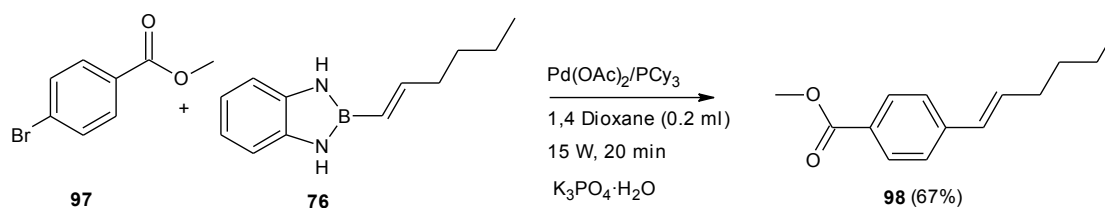


Figure 18: HRMS of compound **96**

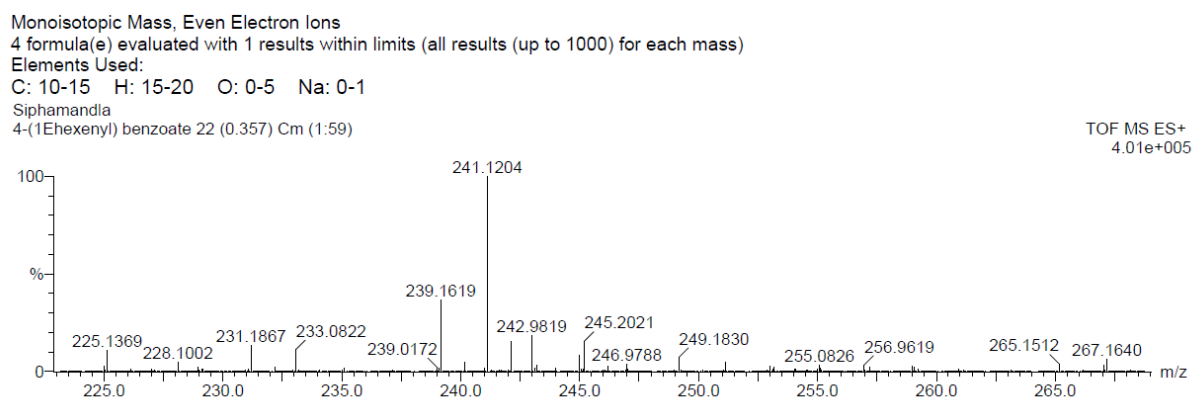
### 2.5.3.4 Synthesis of 4-(1*E*-hexenyl)-methylbenzoate (**98**)

The reaction of 2-(1*E*-hexenyl)benzo-1,3,2-diazaborole (**76**) with 4-bromomethylbenzoate (**97**), under the representative reaction conditions furnished 4-(1*E*-hexenyl)methylbenzoate (**98**) in 67% yields as a colourless oil (Scheme 35).



**Scheme 35**

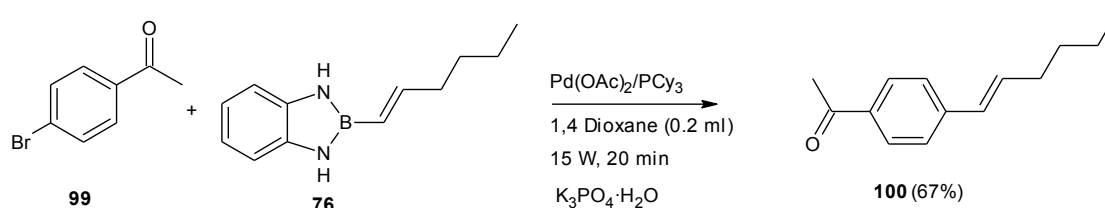
The  $^1\text{H}$  NMR spectroscopic data of the product is consistent with the assigned structure.  $^{13}\text{C}$  NMR spectrum revealed the presence of 12 carbon signals. The HRMS of the product showed a molecular peak  $[\text{M}^+ + \text{Na}^+]$  resonating at  $m/z$  241.1204 which is in agrees well with the calculated  $m/z$  for  $\text{C}_{14}\text{H}_{18}\text{O}_2\text{Na}$  of 241.1204 (**Figure 19**).



**Figure 19: HRMS of compound 98**

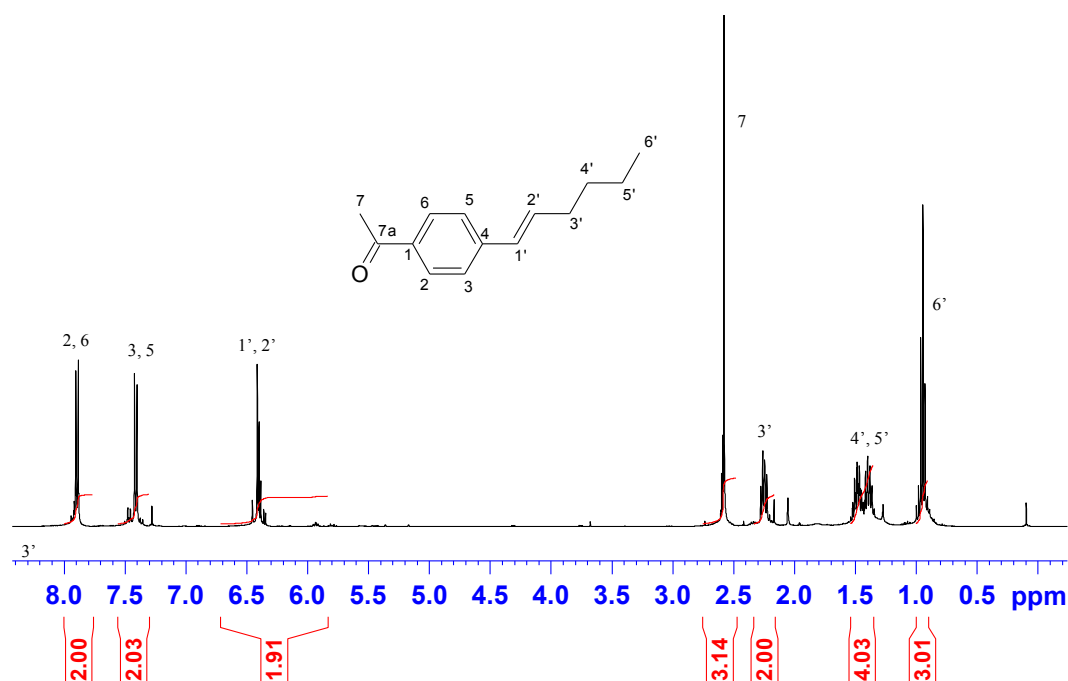
### 2.5.3.5 Synthesis of 4-(1E-hexenyl)-acetophenone (100)

The cross-coupling reaction between 4-bromoacetophenone (**99**) with 2-(1E-hexenyl)benzo-1,3,2-diazaborole (**76**) was successfully achieved under the above mentioned representative procedure. The desired product was obtained in 67% yield (as colourless oil) after purification through silica gel chromatography (**Scheme 36**).



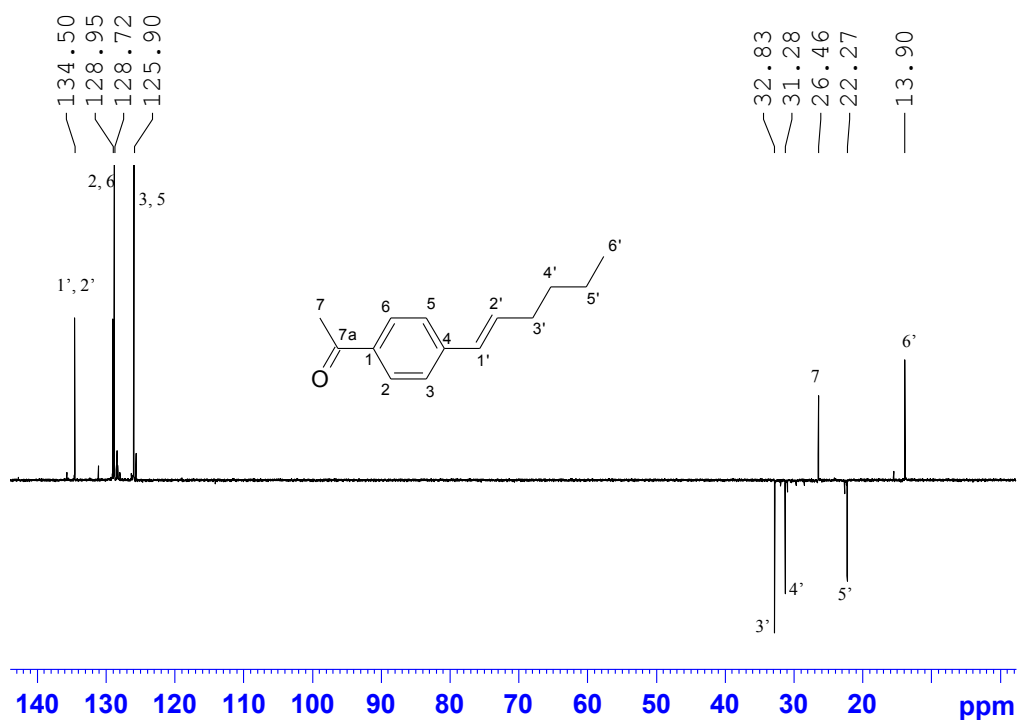
**Scheme 36**

In order to confirm the structure of the product, the  $^1\text{H}$  and  $^{13}\text{C}$  NMR spectra of the colourless oil were acquired. The  $^1\text{H}$  NMR spectrum of the product confirmed the presence of expected number of signals which are consistent with the structure (**Figure 20**).



**Figure 20:**  $^1\text{H}$  NMR spectrum of compound 100

The  $^{13}\text{C}$  (dept-135) NMR spectrum also confirmed that the obtained colourless oil was indeed the assigned product (**Figure 21**). The HRMS data of the product confirmed the molecular formula to correspond to the assigned structure (**Figure 22**).



**Figure 21: DEPT 135 NMR spectrum of compound 100**

Monoisotopic Mass, Even Electron Ions

3 formula(e) evaluated with 1 results within limits (all results (up to 1000) for each mass)

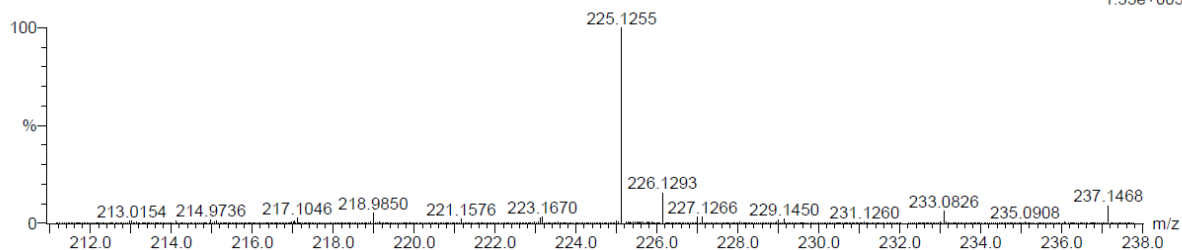
Elements Used:

C: 10-15 H: 15-20 O: 0-5 Na: 0-1

Siphamandla

4-(1Ehexenyl) acetophenone 2 (0.017) Cm (1:59)

TOF MS ES+  
1.35e+005

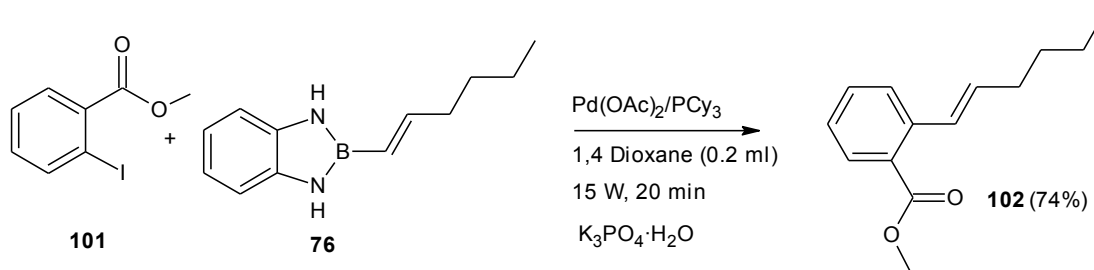


**Figure 22: HRMS of compound 100**

### 2.5.3.6 Synthesis of 2-(1E-hexenyl)-methylbenzoate (102)

2-Iodomethylbenzoate (**101**) was smoothly coupled with 2-(1E-hexenyl)benzo-1,3,2-diazaborole (**76**) following the representative procedure furnished the desired coupled product (**102**) as a colourless oil in 74% yield (**Scheme 37**). The structure of the obtained product was confirmed using  $^1\text{H}$  and  $^{13}\text{C}$  NMR spectroscopy. The  $^1\text{H}$  and  $^{13}\text{C}$  NMR spectra of the product showed the expected peaks which are consistent with the assigned structure. The HRMS revealed a molecular ion peak which resonates at  $m/z$

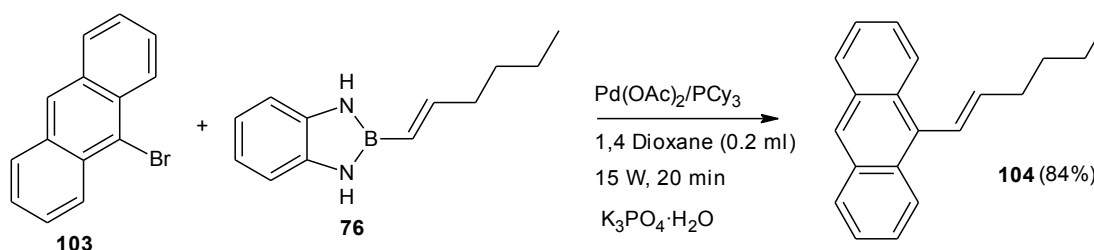
241.1205 which is in excellent agreement with the calculated  $m/z$  for  $C_{14}H_{18}O_2Na$  of (241.1204).



**Scheme 37**

### 2.5.3.7 Synthesis of 9-(1E-hexenyl) anthracene (**104**)

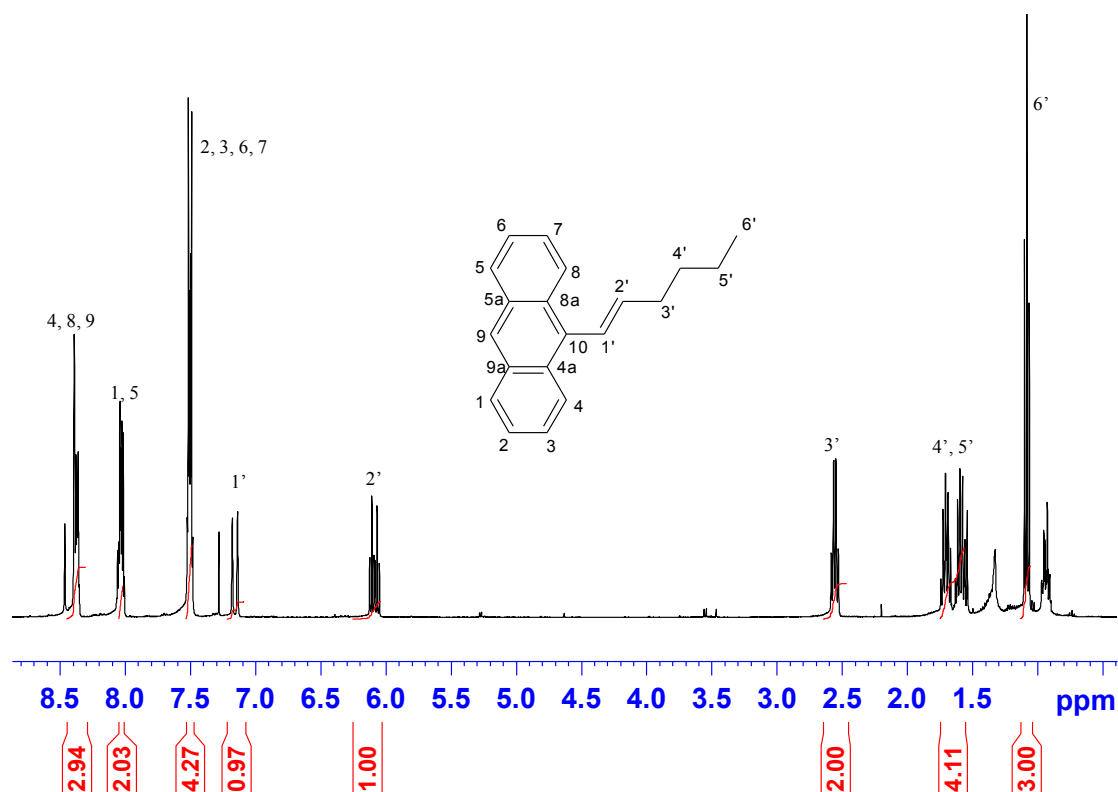
9-(1E-hexenyl)-anthracene (**104**) was synthesised in 84% yield from the cross-coupling reaction of 9-bromoanthracene (**103**) with 2-(1E-hexenyl)benzo-1,3,2-diazaborole (**76**) (**Scheme 38**). The desired product was obtained as a light yellow amorphous solid. The  $^1H$  spectral data of the product is consistent with the structure (**Figure 23**).



**Scheme 38**

The assignment of the desired product was carried out using COSY experiment. According to the COSY spectrum, the triplet resonating at  $\delta$  1.06 ppm (with  $J = 7.3$  Hz) was assigned to 6'-H which was found to be coupled to a multiplet whose signal resonates at  $\delta$  1.52-1.62 ppm (5'-H). The later proton is coupled to a multiplet which is integrating for two (proton 4'-H). The multiplet resonating at  $\delta$  2.58-2.58 ppm is coupled to 4'-H as well as to the doublet of triplet resonating at  $\delta$  6.08 ppm with  $J = 16.1$  Hz. The former proton was therefore assigned to 3'-H. The doublet of triplet at  $\delta$  6.08 ppm was assigned to 2'-H, this protons is also coupled to a doublet of triplet resonating at  $\delta$  7.14 ppm with  $J = 16.0$  Hz (1'-H). The multiplet integrating for four

protons (at  $\delta$  7.46-7.51 ppm) is coupled to the protons whose multiplet appear at  $\delta$  7.99-8.05 ppm (two protons) and  $\delta$  8.32-8.39 ppm (three protons). The multiplet appearing in the region  $\delta$  7.46-7.51 ppm were assigned to 2,-H, 3-H, 6-H and 7-H. 2-H and 6-H are coupled to 1-H and 5-H. The multiplet resonating at  $\delta$  7.99-8.05 ppm (two protons) is assignable to 1-H and 5-H. 3-H and 7-H are coupled to 4-H and 8-H, which in turn suggest that the multiplet resonating at  $\delta$  7.99-8.05 ppm (two protons) is corresponds to 4-H and 8-H. The third proton resonating in the same region ( $\delta$  7.99-8.05 ppm) is only coupled to its self and is therefore assigned to 9-H.



**Figure 23:  $^1\text{H}$  NMR spectrum of compound 104**

The HRMS of the product has a molecular peak with a mass found of 260.1565 which agrees very well with the calculated mass for  $\text{C}_{20}\text{H}_{20}$  of 260.1570 (Figure 2.13b).

Monoisotopic Mass, Even Electron Ions

38 formula(e) evaluated with 1 results within limits (all results (up to 1000) for each mass)

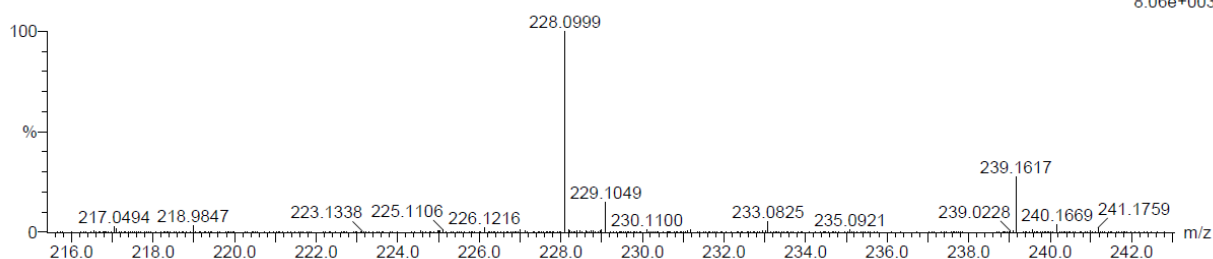
Elements Used:

C: 10-15 H: 10-15 N: 0-5 O: 0-5 Na: 0-1

Siphamandla

4-(1Ehexenyl) Nitrobenzene 12 (0.187)

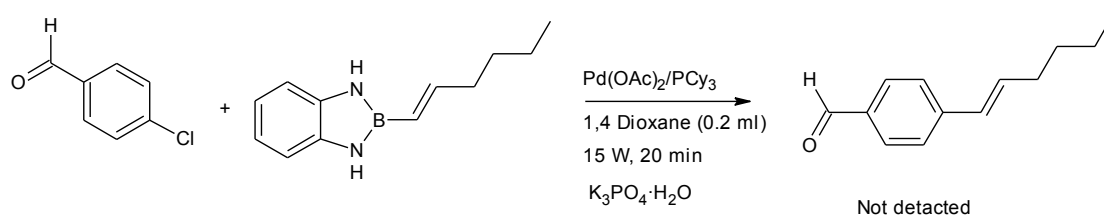
TOF MS ES+  
8.06e+003



**Figure 24: HRMS of compound 104**

### 2.5.3.8 Attempted synthesis of 4-(1E-hexenyl)-benzaldehyde

Unlike the cross-coupling reaction of aryl bromides and iodide, the cross coupling reaction of 4-chlorobenzaldehyde as the electrophilic coupling partners was proven unsuccessful giving no coupled product under the optimal reaction conditions (Scheme 39).



**Scheme 39**

Attempts to increase the reaction time to 40 minutes did not provide any improvements. The slow reactivity of 4-chlorobenzaldehyde under the optimal reaction condition is, however, not surprising since it is well reported in the literature that aryl chlorides are significantly less-reactive because of their sluggish oxidative addition to the palladium metal centre.<sup>69, 86</sup>



## 2.6 Conclusion

From this study, it is concluded that the synthesised 2-benzo-1,3,2-diazaborolane compound is a remarkable hydroborating agent which converts terminal alkenes to their corresponding benzodiazaborolyl derivatives under the influence of Wilkinson's catalyst. The desired cross-coupled products, 2-octylbenzo-1,3,2-diazaborolane (**73**), 2-phenethylbenzo-1,3,2-diazaborole (**74**) and 2-[2-(4-methoxyphenyl)-benzo-1,3,2-diazaborole (**75**) were obtained in 92%, 81% and 79% yields under the optimal reaction conditions, respectively.

On the other hand, 2-benzo-1,3,2-diazaborolane (**79**) was found to be an unsuitable hydroborating agent for the conversion of terminal alkynes to their corresponding alkenylbenzodiazaborolyl derivatives. The use of  $\text{HBBR}_2 \cdot \text{Me}_2\text{S}$  solution as a hydroborating agent and subsequent cyclocondensation of the resulting boronic acid with 1,2-diaminobenzene, on the other hand furnished the desired alkenylbenzodiazaborolyl compound [2-(1*E*-hexenyl)benzo-1,3,2-diazaborole] in 78% yield.

With the 2-alkenyl and 2-alkylbenzo-1,3,2-diazaborole derivatives in hand, the application of these compounds as the Suzuki-Miyaura cross-coupling partners was investigated. The cross-coupling reaction between the synthesized benzodiazaborolyl compounds with a range of aryl halides under the influence of  $\text{Pd}(\text{OAc})_2/\text{PCy}_3$  catalyst appeared facile and versatile. These reactions proceeded smoothly under the influence of the microwave energy furnishing the desired coupled-products in yields ranging from 35% to 84% in less than 20 minutes.

In addition, our standard reaction conditions have proven versatile and general tolerating both the electron-donating and electron-withdrawing functionalities such as -OMe, -NO<sub>2</sub>, -OH, -COOMe and -COMe. Aryl bromides and iodide were successfully converted to the desired products under the coupling conditions; however, aryl chloride failed to afford the expected product due to its sluggish oxidative addition to the palladium centre, as documented in the literature.<sup>69,86</sup>

The results obtained from this project have been drafted in a tetrahedron article and has been published. For reference, a copy of the publication has been attached below

as per Faculty guidelines. Hadebe, S. W., Sithebe, S., Robinson, R. S. *Tetrahedron*, **2011**, *67*, 4277-4282.

## 2.7 References

1. Frankland, E., *J. Chem. Soc.* **1862**, 15, 363.
2. Brown, H. C., Subba, Rao, B. C., *J. Am. Chem. Soc.* **1956**, 78, 5694.
3. Brown, H. C., Zweifel, G., *J. Am. Chem. Soc.* **1960**, 82, 4708.
4. Brown, H. C., Sharp, L. R., *J. Am. Chem. Soc.* **1966**, 88, 5851.
5. Zweifel, G., Ayangar, N. R., Brown, H. C., *J. Am. Chem. Soc.* **1971**, 93, 3395.
6. Gupta, S. K., Brown, H. C., *J. Am. Chem. Soc.* **1971**, 93, 1816.
7. Miyaura, N., Suzuki, A., *Chem. Rev.* **1995**, 95, 2457.
8. Kono, H., Ito, K., *Chem. Lett.* **1975**, 1095.
9. Mannig, D. N., H., *Angew. Chem. Int. Ed. Engl.* **1985**, 24, 878.
10. Evans, D. A., Fu, G. C., Anderson, A., *J. Am. Chem. Soc.* **1991**, 113, 6679.
11. Evans, D. A., Fu, G. C., Hoveyda, A. H., *J. Am. Chem. Soc.* **1992**, 114, 6671.
12. Burgess K., v. d. D., W. A., Westcott, S. A., Mader, T. B., Baker, R. T., Calabrese, J. C., *J. Am. Chem. Soc.* **1992**, 114, 9350.
13. Westcott, S. W., Blom, H. P., Marder, T. B., Baker, R. T., Calabrese, J. C., *Inorg. Chem.* **1993**, 32, 3175.
14. Pereira, S., Srebnik, M., *Organometallics* **1995**, 14, 3127.
15. Pereira, S., Srebnik, M., *J. Am. Chem. Soc.* **1996**, 118, 909.
16. Tucker, C. E., Davidson, J., Knochel, P., *J. Org. Chem* **1992**, 57, 3482.
17. Yamamoto, Y., Fujikawa, R., Umemoto, Y., Miyaura, N., *Tetrahedron* **2004**, 60, 10695.
18. Hadebe, S. W., Robinson, R. S., *Tetrahedron Lett.* **2006**, 47, 1299.
19. Hadebe, S. W., Robinson, R. S., *Eur. J. Org. Chem.* **2006**, 21, 4898.
20. Geier, M. J., Vogels, M. C., Decken, A., Westcott, S. A., *J. Organomet. Chem.* **2009**, 694, 3154.
21. Takacs, M. J., Thacker, N. C., Smith, S. M., *J. Am. Chem. Soc.* **2008**, 130, 3734.
22. Smith, S. M., Takacs, J. M., *J. Am. Chem. Soc.* **2010**, 132, 1740.
23. Lata, C., J., Crudden, M. C., *J. Am. Chem. Soc.* **2010**, 132, 131.
24. Sewell, J. L., Chaplin, A. B., Weller, A. S., *Dalton Trans.* **2011**, 40, 7499.
25. Smith, S. M., Takacs, J. M., Uteuliyev, M., *Chem. Commun.* **2011**, 47, 7812.
26. Mazet, C., Gerard, D., *Chem. Commun.* **2011**, 47, 298.
27. Yuan, Y., Wang, X., Li, Y., Fan, L., Xu, X., Chen, Y., Li, G., Xia, W., *Organometallics* **2011**, 30, 4330.
28. Won, J., Yun, J., Noh, D., Lee, Y. J., *J. Phys. Chem.* **2010**, 114, 12112.
29. Moteki, S. A., Toyama, K., Liu, Z., Ma, J., Holmes, E. A., Takacs, M. J., *Chem. Commun.* **2012**, 48, 263.
30. Harder, S., Spielmann, J., *J. Organomet. Chem.* **2011**, 698, 7.
31. Arrowsmith, M., Hill, S. M., Hadlington, T., Kociok-Kohn, G., Weetman, C., *Organometallics* **2011**, 30, 5556.
32. Wu, Y. J., Moreau, B., Ritter, T., *J. Am. Chem. Soc.* **2009**, 131, 12915.
33. Leyva, A., Zhang, X., Corma, A., *Chem. Commun.* **2009**, 4947.
34. Ely, R. J., Morken, P. J., *J. Am. Chem. Soc.* **2009**, 132, 2534.
35. Khalimon, Y. A., Farha, P., Kuzmina, G. L., Nikonov, G. I., *Chem. Commun.* **2012**, 48, 455.
36. Corberan, R., Mszur, N., W. Hoveyda, H. A., *Angew. Chem. Int. Ed* **2011**, 50, 7079.
37. Sasaki, Y., Horita, Y., Zhong, C., Sawamura, M., Ito, H., *Angew. Chem. Int. Ed* **2011**, 50, 2778.

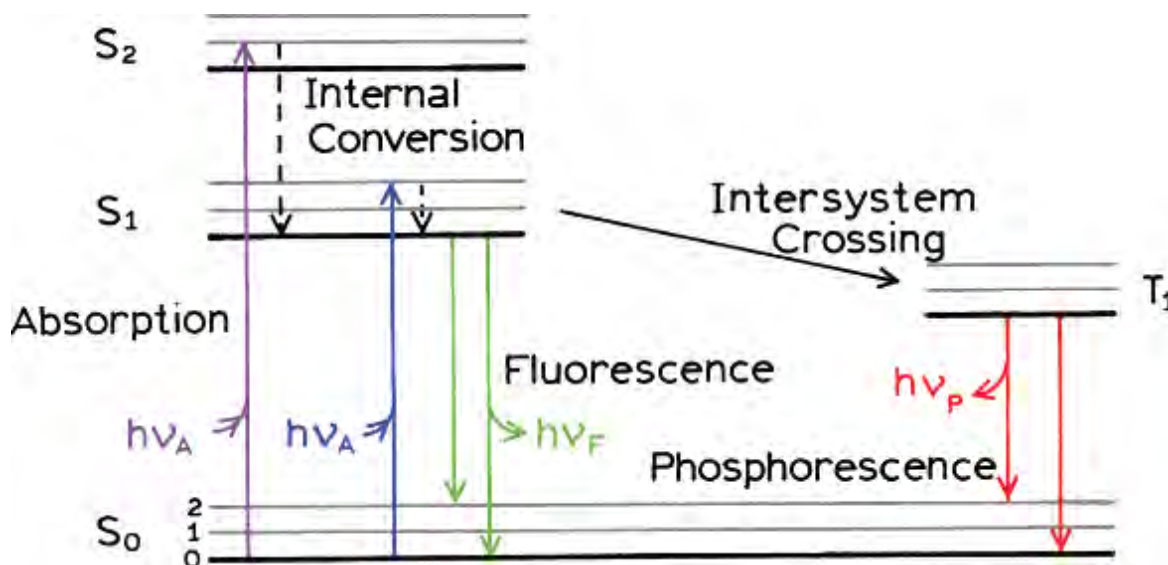
38. Nakagawa, D., Miyashita, M., Tanino, K., *Tetrahedron Lett.* **2010**, 51, 2771.
39. Miyaoura, N., *Cross-Coupling Reactions. A practical Guide, Topics in Current Chemistry*, Springer : Berlin., 2002; Vol. 219.
40. Miyaoura, N., Ishiyama, T., Ishikawa, M., Suzuki, A., *Tetrahedron Lett.* **1986**, 27, 6369.
41. Zou, G., Reddy, Y. K., Falck, J. R., *Tetrahedron Lett.* **2001**, 42, 7213.
42. Rilatt, I., Jackson, R. F.W., *J. Org. Chem* **2008**, 73, 8694.
43. Frisch, A. C., Beller, M., *Angew. Chem. Int. Ed* **2005**, 44, 674.
44. Nethertherton, M. R., Fu, G. C., *Adv. Synth. Catal.* **2004**, 346, 1525.
45. Cardenas, D. J., *Angew. Chem. Int. Ed* **1999**, 39, 3018.
46. Cardenas, D. J., *Angew. Chem. Int. Ed* **2003**, 42, 384.
47. McLaughlin, M., *Org. Lett.* **2005**, 7, 4875.
48. Frsch, A. C., Beller, M., *Angew. Chem. Int. Ed* **2005**, 44, 674.
49. Suzuki, A., *J. Organomet. Chem.* **1999**, 576, 147.
50. Suzuki, A., Sato, M., Miyaoura, N., *Chem. Lett.* **1989**, 1405.
51. Marsden, S. P., Hildebrand, J. P., *Synlett.* **1996**, 898.
52. Charette, A. B., De Freitas-Gill, R. P., *Tetrahedron Lett.* **1997**, 38, 2809.
53. Lohr, S., de Meijere, A., *Synlett.* **2001**, 489.
54. Hartwig, J., Stambuli, J. P., Shelby, Q., Kataoka, N., *J. Org. Chem* **2002**, 67, 5553.
55. Najere, C., Gil-Molto, J., Kalstrom, S., *Adv. Synth. Catal.* **2004**, 346, 1798.
56. Kondolff, I., Doucet, H., Santelli, M., *Tetrahedron* **2004**, 60, 3813.
57. Doucet, H., *Eur. J. Org. Chem.* **2008**, 2013.
58. Brown, H. C., Knights, E. F., Scouten, C. G., *J. Am. Chem. Soc.* **1974**, 96, 7765.
59. Thomas, S. E., *The role of boron and silicon*, Oxford University press New York, 1994.
60. Potuzak, J. S., Tan, D. S., *Tetrahedron Lett.* **2004**, 45, 1797.
61. Fu, G. C., Nethertherton, M. R., Dai, C., Neuschuetz, K., *J. Am. Chem. Soc.* **2001**, 123, 10099.
62. Kirchhoff, J. H., Dai, C., Fu, G. C., *Angew. Chem. Int. Ed* **2002**, 41, 1945.
63. Capretta, A., McNulty, J., Robertson, A., Britten, J., Frampton, C. S., Adjabeng, G. M., Gerristma, D. A., Brenstrum, T., *J. Org. Chem* **2004**, 69, 7635.
64. Flaherty, A., Trunkfield, A., Barton, W., *Org. Lett.* **2005**, 7, 4975.
65. Achonduh, G. T., Hadei, N., Velente, C., Avola, S., O'Brien, C., J., Organ, M., G., *Chem. Commun.* **2010**, 46, 4109.
66. Fu, G. C., Le, Z., *Angew. Chem. Int. Ed* **2010**, 49, 6676.
67. Fu, G. C., Le, Z., Wilsily, A., *J. Am. Chem. Soc.* **2011**, 133, 8154.
68. Taylor, B. L. H., Jarvo, E. R., *J. Org. Chem* **2011**, 76, 7573.
69. Molander, G. A., Ito, T., *Org. Lett.* **2001**, 3, 393.
70. Molander, G. A., Yun, C. -S., Ribagorda, M., Biolatto, B., *J. Org. Chem* **2003**, 68, 5534.
71. Jana, R., Pathak, T. P., Sigman, S. M., *Chem. Rev.* **2011**, 111, 1417.
72. Charette, A. B., Mathieu, S., Fournier, J.-F., *Synlett.* **2005**, 1779.
73. Molander, G. A., Petrillo, D. E., *Org. Lett.* **2008**, 10, 1795.
74. Nie, H.-J., Yao, J., Zhong, Y.-W., *J. Am. Chem. Soc.* **2011**, 76, 4771.
75. Dreher, D. S., Lim, S.-Ee., Sandrock, L. D., Molander, G. A., *J. Am. Chem. Soc.* **2009**, 74, 3626.
76. Lillo, V., Mata, J. A., Segarra, E., Peris, E., Fernandez, E., *Chem. Commun.* **2007**, 2184.
77. Hadebe, S. W., Sithebe, S., Robinson, R. S., *Tetrahedron* **2011**, 67, 4277.
78. Brown, H. C., Campbell, J. B., *J. Org. Chem* **1975**, 45, 389.
79. Nethertherton, M. R., Fu, G. C., *Angew. Chem. Int. Ed* **2002**, 41, 3910.
80. Molander, G. A., Ellis, N., *Acc. Chem. Res.* **2007**, 40, 275.
81. Denk, M. K., Organometallics Compounds of Boron and Aluminium Chapter 3, [www://131.104.156.23/Lecture/331/331Chapter3.html](http://www.131.104.156.23/Lecture/331/331Chapter3.html). Date accessed: 25-04-2010. In.

82. Soderquist, J. A., Matos, K., , *J. Org. Chem* **1998**, 461.
83. Jourdent, A., Conzalez-Zamora, E., Zhu, J., *J. Org. Chem* **2002**, 67, 3163.
84. Serijan, K. T., Wise, P. H., *J. Am. Chem. Soc.* **1951**, 73, 4766.
85. Felpin, F.-X., Fouquet, E., *Chem.-Eur. J.* **2010**, 16, 12440.
86. Saito, S., Oh-tani, S., Miyaura, N., *J. Org. Chem.* **1997**, 62, 8024.

## Chapter Three

### *General Fundamentals of Fluorescence*

The photophysical excitation and deactivation processes that occur during absorption and emission of light, from a fluorophore, are best illustrated by Jablonski diagram (Figure 25).<sup>1</sup>



**Figure 25. The Jablonski diagram (taken from reference 4).**

The diagram depicts three vibrational energy levels with electronic singlet states  $S_0$ ,  $S_1$ ,  $S_2$  and triplet state  $T_1$ , respectively. According to Boltzmann statistics, 99% of the electrons occupy the lowest vibrational level of  $S_0$  at room temperature. During the excitation process, the electrons are promoted from their most stable ground electronic state  $S_0$  to the higher first  $S_1$  and second  $S_2$  electronic states. The vertical lines labelled  $h\nu_A$  illustrate the transition of electrons from  $S_0$  to the higher vibrational energy level as a consequence of light absorption.<sup>1</sup> Depending on the amount of light (or energy) absorbed, the excited electrons can occupy any of the vibrational levels of  $S_1$  (or  $S_2$ ). Since emission occurs from the lowest vibrational level of  $S_1$  (Kasha's rule), electrons excited to the second vibrational level ( $S_2$ ) and/or to the higher vibrational level of  $S_1$ , rapidly relaxes to the lowest level of  $S_1$  via a non-radiative process called Internal Conversion (IC). After IC, almost all the electrons have fully returned to the lowest level of  $S_1$ . At this point, some electrons undergo Intersystem

Crossing (ISC) which is another non-radiative process that involves a spin conversion from the singlet state ( $S_1$ ) to a triplets state ( $T_1$ ).

Deactivation of electrons from either  $S_1$  or  $T_1$  to the ground state ( $S_0$ ) follow a radiative process called photoluminescence.<sup>2</sup> Photoluminescence is divided into (i) fluorescence and (ii) phosphorescence, depending on the nature of the excited state and the behaviour of an excited electron upon deactivation to the ground state.<sup>3</sup> Fluorescence is the emission of light accompanying the deactivation of excited electrons to a ground state of the same multiplicity (i.e.  $S_1 \rightarrow S_0$ ). The excited electrons are spin paired to electrons in the ground state, thus making fluorescence a spin-allowed transition.<sup>4</sup> Phosphorescence is the emission of light as a result of deactivation of excited electrons to the ground state of different multiplicity ( $T_1 \rightarrow S_0$ ). The excited electrons have the same orientation to electrons in the ground state thus making phosphorescence a spin-forbidden process.<sup>5</sup>

The energy lost through non-radiative processes (IC and ISC) is the reason why the observed emission spectrum occurs at a longer wavelength (lower energy) than the absorption spectrum i.e. Stokes Shifts. The larger the Stokes Shifts the larger is the energy lost by excited electron through nonradiative processes. There are several processes that facilitate the loss of energy through non radiative pathways (which in turn, lead to large Stokes Shifts). These include: solvent orientation effect, change in geometry (and thus the dipole moment) of the molecule upon excitation, complex formation or decomposition of the fluorophore<sup>\*</sup> in the excited state as a result of the absorption of energy.

For practical purposes (see the introduction below), Stokes Shift is a measure of a difference between the absorption and the emission wavelength maxima, and the larger the value of the Stokes Shift the better is the sensitivity of a fluorophore towards any small photophysical changes.

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<sup>\*</sup> Fluorophore is any functional group that is responsible for the absorption and emission of light during photophysical process.

Since only a fraction of the excited electrons relax through fluorescence (see figure 3.1), the Stokes Shift is usually accompanied by another photophysical parameter known as fluorescent quantum efficiency or yield ( $\Phi$ ). Basically,  $\Phi$  measures the efficiency or the quality of photophysical excitation and deactivation processes. In practice,  $\Phi$  reflects the brightness of the emission (light emitted after excitation), and is defined as the ratio of photons absorbed to photons emitted through fluorescence. Since fluorescent quantum yield is defined as a ratio, this parameter ranges from zero to one. As a consequence, a fluorophore with a fluorescent quantum yield approaching one displays the brightest emission. Similar to the Stokes Shifts, for practical application, the higher the value of  $\Phi$  the better is the photophysical and optical properties of the responsible fluorophore (see introduction for more details).

### 3 Introduction

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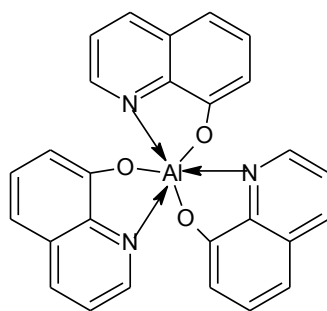
Light emitting-diodes (LEDs) based on small compounds typically requires three layers for high output performance of a device, these include (i) electron transporting layer, (ii) emissive layer and (iii) a hole transporting layer, of which the latter, is intended to facilitate the charge transport thus enhancing the quality of the device.<sup>6</sup> Inorganic nanocrystals have extensively been investigated because of their intriguing electro and photoluminescence properties, which are important for emitters in light emitting diodes devices.<sup>7</sup>

Some of the important requirements for high output efficiency in Light emitting-diodes (LED) include their ability to transport electrons, to emit different colours and to possess high fluorescence quantum yields. Researchers have, however, shown that inorganic nanocrystals are not only poor in displaying multicolour (including blue), but are also poor emitters (i.e. they possess low fluorescent quantum yields).<sup>8</sup>

On the other hand, a large number of organic compounds have been shown to have extremely large fluorescent quantum yields and are able to display multicolour including the blue luminescence.<sup>9</sup> For these reasons, some organic compounds have been considered as possible candidate for application in LED. However, only limited progress has been achieved in the development of organic LED due to the high voltage required for brightest colour display and low stability of organic light emitting diodes (OLED). Early attempts made by Helfrich *et al.* (1965)<sup>10</sup> to overcome such obstacles failed to improve the luminescent properties of organic light-emitting diodes (OLEDs).

It wasn't until 1987 that OLED gained popularity when Tang and VanSlyke reported, for the first time, an organic compound with improved luminescent properties. Tang and VanSlyke<sup>11</sup> documented that aluminium tris-8-hydroxyquinoline (**Alq<sub>3</sub>**) (**Figure 26**) requires low voltage for the brightest blue colour display and it is also more stable compared to previously investigated organic compounds, thus making **Alq<sub>3</sub>** an ideally suitable emitting layer in LED.<sup>11</sup>



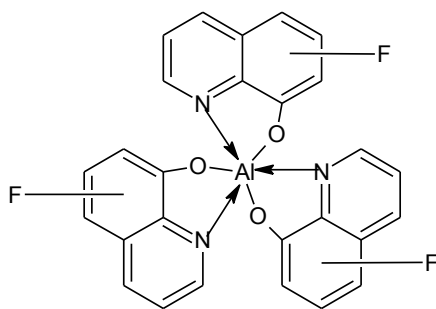


**Figure 26: Structure of Alq<sub>3</sub>**

Since the original report by Tang and VanSlyke, a lot of effort has been concentrated at developing alternative compounds to **Alq<sub>3</sub>** in order to expand the number of colours emitted and to further improve the luminous efficiency of OLEDs. To gain detailed understanding into the structural and molecular properties of **Alq<sub>3</sub>**, Corioni *et al.*<sup>12</sup> and Burrows *et al.*<sup>13</sup> independently conducted the molecular orbital studies on **Alq<sub>3</sub>**. In their studies, they reported that both HOMO and LUMO of **Alq<sub>3</sub>** are localized on the 8-hydroxyquinoline ligand.<sup>14</sup>

Logically, one approach to improve the photoluminescence properties of **Alq<sub>3</sub>** has been to substitute 8-hydroxyquinoline with different ligands or to use chemically modified 8-hydroxyquinoline ligands. With these ideas in mind, a lot of researchers directed their research focus towards the investigation of substituted 8-hydroxyquinoline ligands on the luminescence properties of **Alq<sub>3</sub>**.<sup>15</sup> Recently, Shi *et al.*<sup>16</sup> have synthesised fluorinated **Alq<sub>3</sub>** derivatives hoping that the fluorinated **Alq<sub>3</sub>** will have the improved absorption and emission properties compared to **Alq<sub>3</sub>**.

However, fluorination did not improve the optical characteristics of **Alq<sub>3</sub>** but instead it resulted in a significant decrease in the intensity of the emission peak and a tremendous loss in the photoluminescence efficiency of the fluorinated derivatives (**FAlq<sub>3</sub>**) (**Figure 27**).<sup>16</sup>

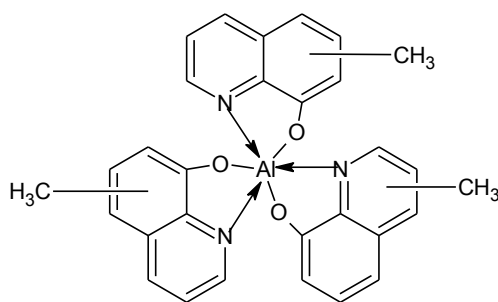


**Figure 27: Structure of fluorinated Alq<sub>3</sub>**

The loss in luminous efficiency of fluorinated derivatives (**FAlq<sub>3</sub>**) has been rationalised to originate from the electron-withdrawing inductive effect of the fluorine atoms which widens the HOMO-LUMO energy gap on the fluorinated 8-hydroxyquinoline ligands, resulting in a hypsochromic shift (which is the shift of an absorption or an emission maxima to the shorter wavelength) of the emission peaks of **FAlq<sub>3</sub>** relative to **Alq<sub>3</sub>**.<sup>16</sup>

In order to investigate the influence of the electron-donating substituents on the spectroscopic properties of **Alq<sub>3</sub>** derivatives, Sapochak *et al.*<sup>17</sup> and Chen *et al.*<sup>18</sup> soon synthesised and studied the spectroscopic properties of methylated **Alq<sub>3</sub>** derivatives. Their studies independently revealed that substitution of hydrogen atoms with weakly electron-donating methyl groups, on both the phenoxide or on the pyridyl ring of 8-hydroxyquinoline ligand considerably improved the spectroscopic properties of **Alq<sub>3</sub>**.<sup>19,20</sup> The large enhancement in the photoluminescence quantum efficiency observed for methylated derivatives (**MeAlq<sub>3</sub>**, Figure 3.4) was reported to be due to the elevation of both HOMO and LUMO energy levels of **MeAlq<sub>3</sub>**. This effect improves  $\pi$ -communication between the ligand and the metal atom.

Sapochak *et al.*<sup>17</sup> also pointed out that the high fluorescent quantum efficiency displayed by **MeAlq<sub>3</sub>** was partly attributed to less energy lost in an excited state of **MeAlq<sub>3</sub>** due to fewer paths available for nonradiative decay as suggestive of a small stokes shift exhibited by **MeAlq<sub>3</sub>** compared to that of **Alq<sub>3</sub>**.<sup>17</sup>



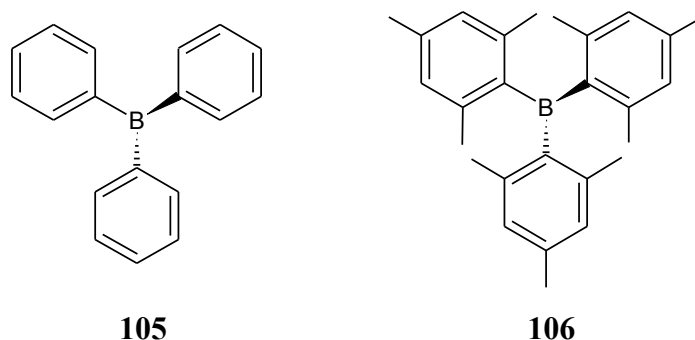
**Figure 28: Structure of methylated Alq<sub>3</sub>**

Another approach to improve photophysical properties of **Alq<sub>3</sub>** has been to substitute the central aluminium atom with other elements. A range of metal ions have been complexed with different ligands, however, most of the resulting complexes, especially with heavy metals, such as copper, magnesium, calcium and strontium have proven to be less fluorescent than **Alq<sub>3</sub>** thus making them unsuccessful for OLED applications.<sup>21,22</sup> Recently, boron complexes have drawn a great deal of attention due to their outstanding photophysical, electron transporting, absorption and luminescent properties when compared to aluminium complexes.<sup>23</sup>

### 3.1 Three Coordinate Boron Complexes

With the empty  $2p_z$ -orbital on the central boron atom, organoboron complexes are electron deficient and are therefore considered as strong  $\pi$ -electron acceptors. These unique properties have been shown to facilitate extensive delocalisation when attached to organic  $\pi$ -system. In addition, Williams and co-worker<sup>24</sup> also reported that, unlike other strong  $\pi$ -electron acceptors, boron atoms also possess a  $\sigma$ -donor characteristics which promote better orbital overlap between  $2p_z$ -orbital of boron and adjacent atoms thus making organoboron complexes more suitable for application in OLEDs.<sup>24</sup>

Despite the exceptional fluorescent characteristics displayed by organoboron complexes, it is however, well documented in the literature that most organoborane compounds are susceptible to nucleophilic, electron donor molecules such as water and other donor solvents resulting in either degradation or the formation of non-fluorescent species.<sup>24</sup> Doty and co-worker<sup>25</sup> who were interested in the photochemistry studies of organoboron complexes also confirmed that triphenylborane (**Figure 29**) was indeed prone to photodegradation in the presence of nucleophilic solvents.<sup>25</sup>

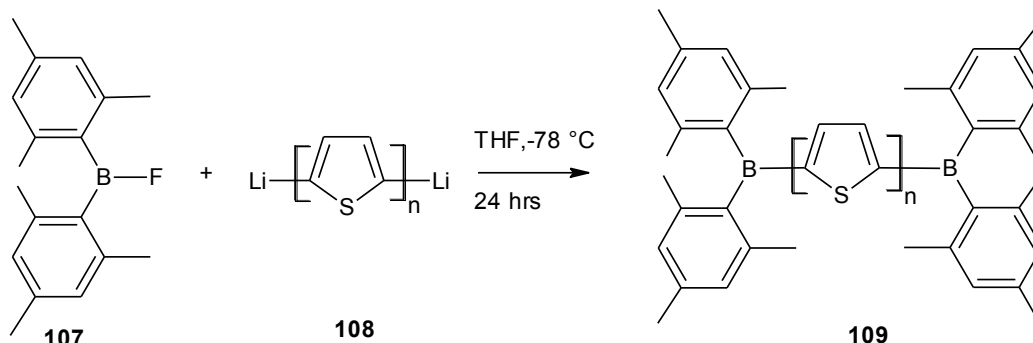


**Figure 29: Structures of three coordinate boron complexes**

To overcome such complications, Dots *et al.*<sup>26</sup> discovered that the use of bulky aromatic groups such as mesityl (2,4,6-trimethylphenyl) provided trimesitylborane (**106**) with an unusually high degree of stability when compared to triphenylborane (**105**).<sup>26</sup> According to Dots and co-workers, the high stability possessed by trimesitylborane is attributed to steric hinderance brought by *ortho*-methyl substituents on the aryl rings which shield the vacant  $p_z$  orbital from nucleophilic

attack by blocking the approach of nucleophiles. After these discoveries, the chemistry of mesityl containing borane complexes has since been the subject of a great deal of interest due to their pronounced stability as well as intriguing photophysical properties. With this strategy, tremendous progress has been achieved in the development of robust materials for potential applications in OLED. These developments have successfully led to the design and the synthesis of numerous boron containing complexes which are ideal for use as multicolour emissive and electron transporting layers for OLEDs. For example, in the emissive category, Jia's group<sup>27</sup> and others<sup>28</sup> have recently demonstrated the synthesis of boron containing complexes that exhibits blue, green and red photoluminescence with high fluorescent quantum yields.<sup>27</sup>

In 1998, Shirota and Noda<sup>29</sup> were amongst the first to design and synthesise the electron-transporting mesitylborane complexes that function as charge carriers in OLEDs.<sup>30</sup> **BMB-2T (109a)**<sup>†</sup> and **BMB-3T (109b)**<sup>‡</sup> were synthesized in 40 and 30 % yields from the cross-coupling reaction of dimesitylboron fluoride (**107**) with the lithiated oligothiophene (**108**), respectively (**Scheme 40**).<sup>31</sup>



**Scheme 40**

According to Shirota and Noda,<sup>29</sup> **BMB-2T** and **BMB-3T** are excellent electron transporting molecules because these compounds were carefully constructed in such a way that oligothiophene moieties function as electron-donor whereas the dimesitylboroane group provide electrons-accepting properties. The incorporation of

<sup>†</sup> 5,5'-bis(dimesitylboryl)-2,2'-bithiophene (**BMB-2T**) where *n* = 2

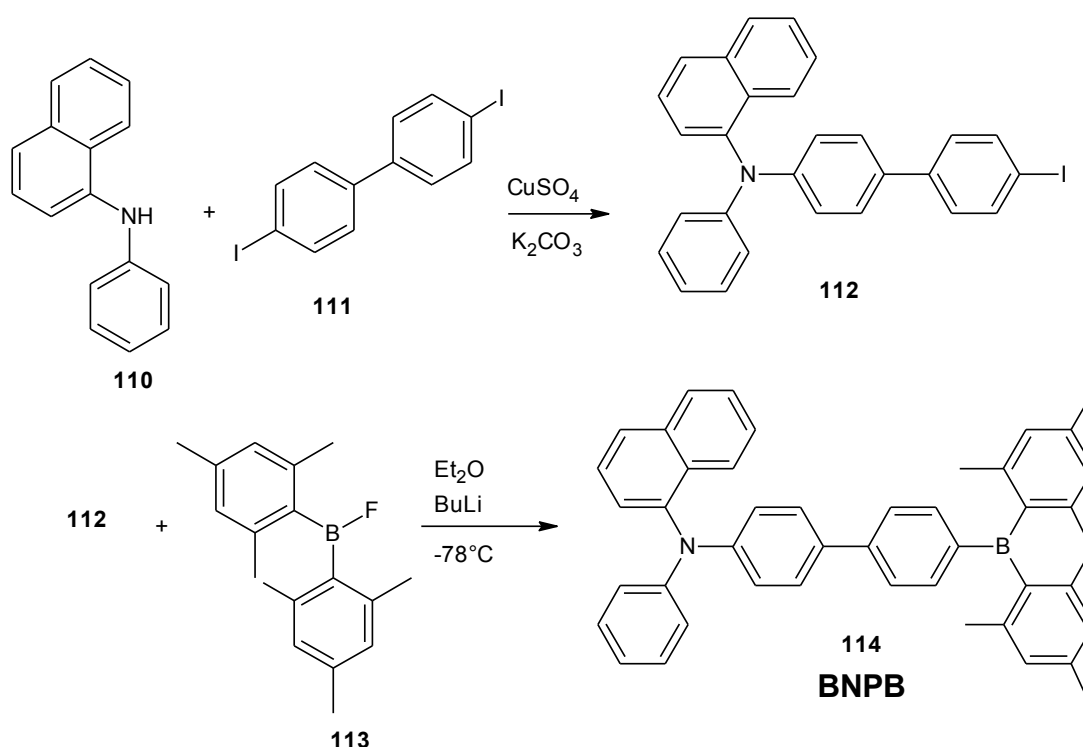
<sup>‡</sup> 5,5'-bis(dimesitylboryl)-2,2':5', 2''-bithiophene (**BMB-3T**) where *n* = 3

both electron donor and electron acceptor groups within one molecule was the key for electron transporting properties exhibited by these compounds.<sup>29</sup>

The findings of Shirota and Noda presented a new approach for molecular design and the development of new electron-transporting organoboron complexes with exceptional properties. In 2003, Dots *et al.*<sup>32</sup> also reported that one way of enhancing the overall efficiency of LED devices is to reduce the number of layers used in OLED. According to Doi *et al.*,<sup>32</sup> this can effectively be done by designing molecules which are capable of functioning both as emitters as well as electron-transporting materials. Two years later, Wang *et al.*<sup>33,34</sup> confirmed the hypothesis proposed by Doi *et al.*<sup>32</sup> when they demonstrated that compounds with both electron-accepting boron centre and electron-donating triarylamine do not only effectively transport electrons but they also show strong luminescence, making them attractive for applications in advanced material science.<sup>33,34</sup> For example, their group showed that, a good electron transporting complex **BNPB**<sup>\*</sup> is also capable of displaying a bright blue luminescence, thus making this compound an excellent emitter as well.<sup>33</sup> **BNPB** was synthesised in 89% from the cross-coupling reaction of 4-iodo-4'-(naphthylphenylamino)-biphenyl (**112**) with dimesitylboron fluoride **3b'** in diethyl ether. The reaction of 1-naphthylphenylamine (**110**) with 4,4'-biphenyl iodine (**111**), under Ullmann condensation reaction conditions, afforded 4-iodo-4'-(naphthylphenylamino)-biphenyl (**112**) (**Scheme 41**).

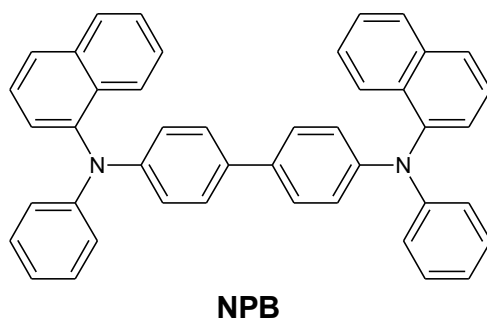
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\* (Mes<sub>2</sub>B[*p*-4,4'-biphenyl-NPh(1-naphthyl)] (**BNPB**)



**Scheme 41**

Wang *et al.*<sup>33</sup> reported that the emission spectra of **BNPB** displays a bathochromic shift (shift of the absorption or the emission maxima to the longer wavelength) with increasing solvent polarity (i.e. solvatochromism). According to Wang *et al.*,<sup>33</sup> the solvatochromism shown by **BNPB** was attributed to the presence of a more excited state than the ground state, which suggests the involvement of the charge transfer from the electron rich (HOMO) amino group to the electron poor (LUMO) dimesitylboron group. Photoluminescence, as a result of charge transfer, has been reported to be brighter than the light emitted as a consequence of electrons transition from HOMO to LUMO, hence making **BNPB** is a brighter emitter both in solid state and in solution.<sup>33</sup> Despite the excellent emissive properties exhibited by **BNPB**, comprehensive studies conducted by Wang *et al.*<sup>33</sup> soon revealed that the overall performance of **BNPB** is lower than the performance of commercialised electron-transporting **NPB** previously reported by Tse *et al.*<sup>35</sup> (**Figure 30**).



**Figure 30: Structure of NPB**

To improve the performance of **BNPB** to match that of **NPB**, Wang and co-workers modified **BNPB** by increasing the number of **NPB** functional groups which enhance the electron transporting capabilities of **BNPB**. They also introduced *para*-duryl groups to create more steric congestion around the boron centre.<sup>33</sup> With this new strategy, the group designed and synthesised tris[*p*-(1-naphthylphenylamino)phenylduryl]borane (**B(dp-NPB)<sub>3</sub>**) hoping that this new compound will show improved photo as well as electrochemical properties when compared to **BNPB**. For the synthesis of **B(dp-NPB)<sub>3</sub>** (**118**), the starting material *p*-(1-naphthylphenylamino)-phenyl bromide (**115**) was first converted to the corresponding *p*-(1-naphthylphenylamino)-phenylboronic acid (**116**) which was subsequently coupled with B(*p*-duryl-I)<sub>3</sub> (**117**) under the Suzuki-Miyaura cross-coupling reaction conditions in the presence of a catalytic amount of Pd(PPh<sub>3</sub>)<sub>4</sub> and Na<sub>2</sub>CO<sub>3</sub> as a base (**Scheme 44**).<sup>33</sup>





**BNPB** (2.90 eV). These results clearly indicated that **B(dp-NPB)<sub>3</sub>** was not only a poor emitter, but was also a poor electron transporting material compared to **BNPB**. The large optical band and the hypsochromic shift of the absorption maximum observed for **B(dp-NPB)<sub>3</sub>** was attributed to the lack of  $\pi$ -communication between the three aminoaryl groups and the central boron atom.<sup>33</sup> The diminished  $\pi$ -conjugation between the two groups was due to the replacement of the phenyl spacer by the duryl groups as reported by Wang *et al.*<sup>33</sup>

Over the past decade, extensive research has been concentrated on the improvement of the existing fluorescent based compounds for application in OLED. These developments have resulted in a large number of publications reporting the investigation of organic compounds with the same design and structural motif.<sup>36,37</sup>

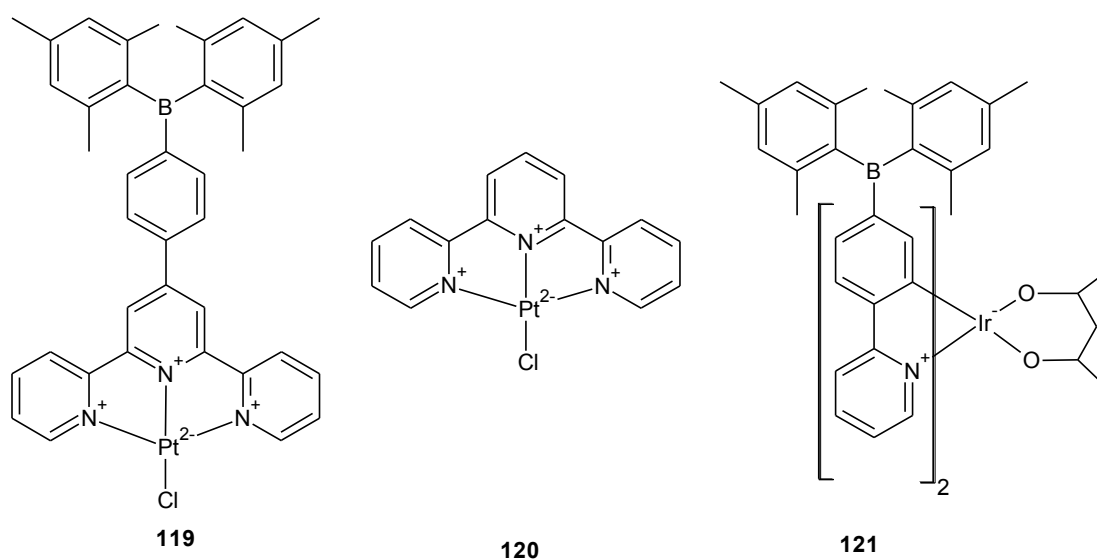
However more recently, Lowry *et al.*<sup>38</sup> have demonstrated that one way of improving the OLED performance is to design compounds which can be able to display photophysical and electrophysical properties based on phosphorescence phenomenon.<sup>39</sup> This idea of was further supported by the work of Yang *et al.*<sup>40</sup> who revealed that some metal complexes, especially iridium based complexes, display bright phosphorescent emission which could be of use in the development of future OLEDs.

Chujo and the co-worker<sup>41</sup> were the first to report that mesitylborane group could greatly facilitates metal-to-ligand charge transfer (MLCT)<sup>†</sup> in most transition metal complexes.<sup>41</sup> Kitamura *et al.* further confirmed the existence of this phenomenon when they demonstrated that the incorporation of boryl moiety greatly enhances MLCT bands resulting in tenfold increment of the emission brightness of **119** over that of **120** (**Figure 31**).<sup>42</sup> Two years later, Marder and co-workers<sup>43</sup> reported complex **121** to display bright red phosphorescence at 605 nm which is red shifted compared to the parent compound Ir(ppy)<sub>2</sub>(acac) (516 nm), this was attributed to the stabilisation of MLCT state by BMes<sub>2</sub> group<sup>‡</sup>.<sup>43</sup>

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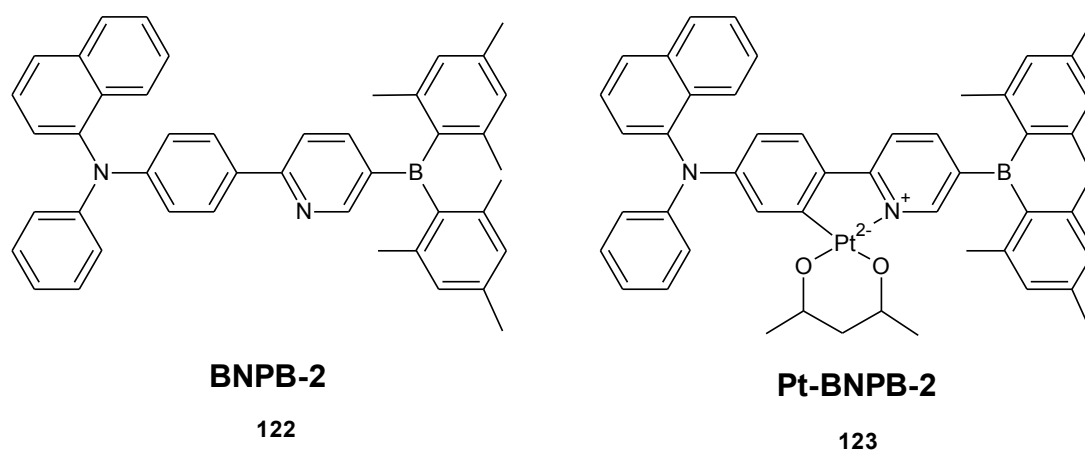
<sup>†</sup> MLCT transition has been reported to be responsible for an intense emission commonly displayed by triarylboron containing metal complexes. These emissions (phosphorescent based emissions) are more intense than the mostly investigated fluorescent based emissions, making phosphorescent compounds more ideal as emissive material in OLED.

<sup>‡</sup> Dimesitylborane group.



**Figure 31: Structure of platinum arylboranes**

Hudson *et al.*<sup>44,45</sup> who intensively investigated the photophysical properties of a blue emitter as well as a charge carrier **BNPB-2**, also emphasised the remarkable impact of MLCT on the photophysical properties of **BNPB-2**. The ligand **BNPB-2** shows a bright blue fluorescent emission at 365 nm in CH<sub>2</sub>Cl<sub>2</sub>. Upon platinum chelation, the complex (**Pt-BNPB-2**) displayed a bright orange phosphorescence.<sup>45</sup> **Pt-BNPB-2** exhibited the highest efficiency and an impressive performance when it was evaluated as an emitter for OLED, making this complex a possible candidate for commercialised devices (figure 3.8).<sup>45</sup>

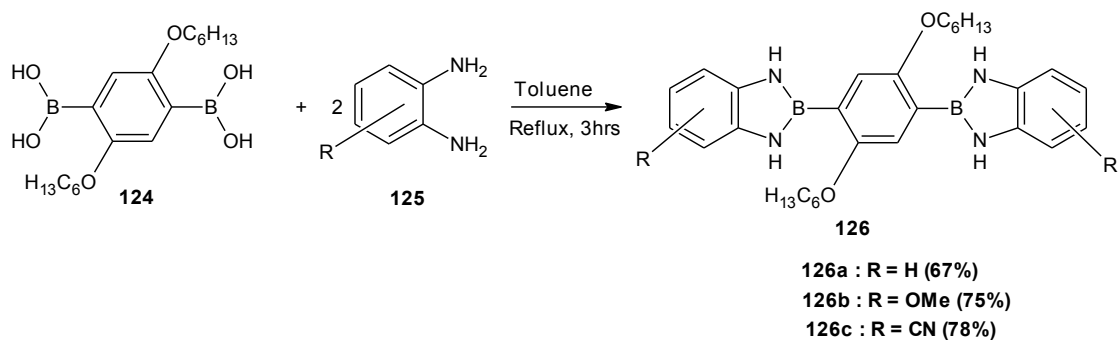


**Figure 32: Structures of BNPB-2 and Pt-BNPB-**

## 3.2 Benzo-1,3,2-Diazaborolyl-Functionilized Complexes

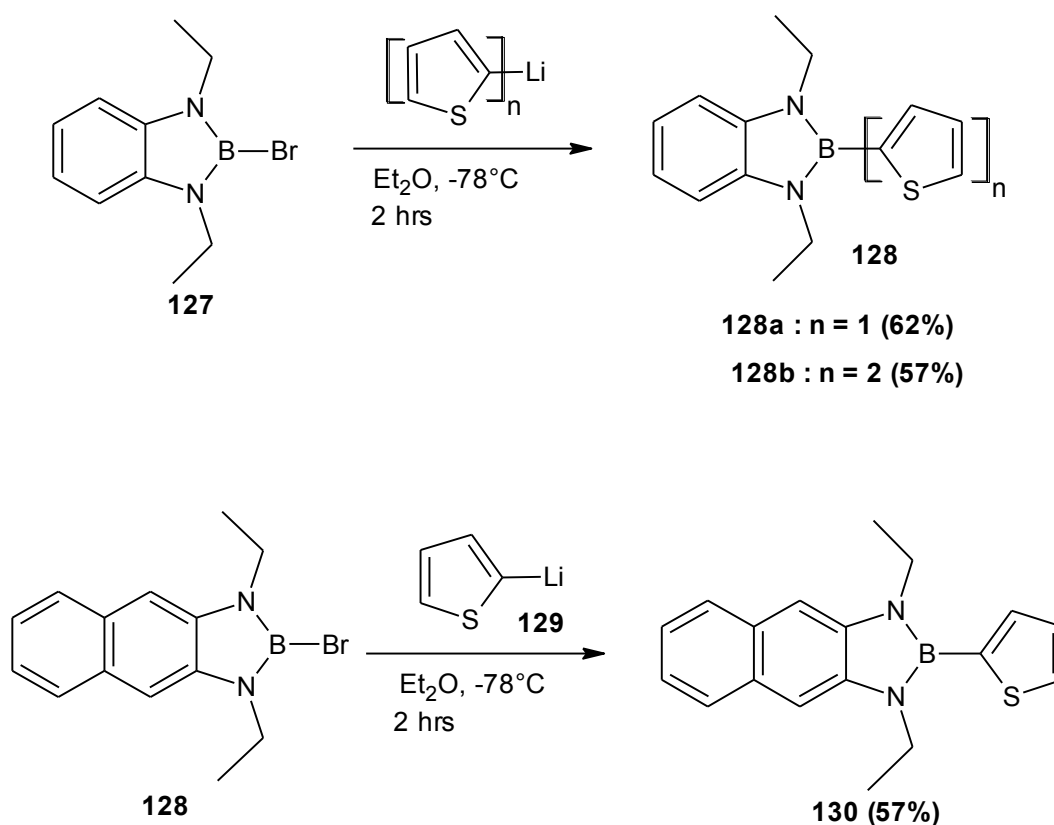
Molecular compounds functionalised with 1,3,2-diazaborolyl groups have received considerable attention and have been investigated for their optical, electronic and ion sensing abilities, making them possible candidates for use in advanced material science. More has witnessed rapid developments in the chemistry of 1,3,2-diazaborolyl containing compounds due to their photoluminescence characteristics and unusual stability. Unlike most triarylborane compounds, which require dimesitylborolyl moieties for the enhancement of their stability, 1,3,2-benzodiazaborole based compounds have been reported to be water and air stable without any addition of dimesityl groups. To get an insight into understanding the intriguing characteristics exhibited by these compounds, Maruyama and Kawanishi<sup>46</sup> investigated the effect of the donor and/or acceptor substituents on the absorption and emission properties of 1,3,2-diazaborolyl containing compounds.

In order to compare the absorption and the emission maxima, Maruyama and Kawanishi synthesised compounds **126a-c** from the cyclocondensation reaction of 2,5-alkoxy-1,4-phenylenediboronic acid (**124**) with the corresponding 1,2-phenylenediamine (**125**) and acquired their spectra data (**Scheme 45**). Their results showed that the absorption maximum for compound **126b** ( $\lambda_{\text{max,abs}} = 351 \text{ nm}$ ) experienced a bathochromic shift compared to that of **126a** ( $\lambda_{\text{max,abs}} = 315 \text{ nm}$ ), whereas the absorption maximum for **126c** ( $\lambda_{\text{max,abs}} = 291 \text{ nm}$ ) showed a hypsochromic shift compared to that of **126c**. Maruyama and kawanishi attributed to the red-shift showed by compound **126b** to be attributed to the donor effect of the methoxy group which mesomerically donates electrons to the molecules. This phenomenon has been demonstrated to narrow the HOMO-LUMO gap thus shifting the absorption maximum of **126b** to a longer wavelength relative to that of **126a**.<sup>46</sup>



**Scheme 45**

The foundation laid by Maruyama and Kawanishi was further expanded by Domke *et al.*<sup>47</sup> Domke *et al.* investigated the influence of increasing the conjugation length either at the backbone or at the 2-position of the synthesized compounds. According to these authors the reaction of 2-bromo-1,3,2-diazaborolane (**127**) with the corresponding thienyl lithium afforded the desired compounds in yields ranging from 57% (**130**) to 62% (**127a**) (**Scheme 46**).<sup>47</sup>



**Scheme 46**

The results from the photophysical studies conducted by Domke *et al.*<sup>47</sup> on thiophene-functionalised diazaborole compounds **128a**, **128b** and **130** are summarised in table 3.1 below.

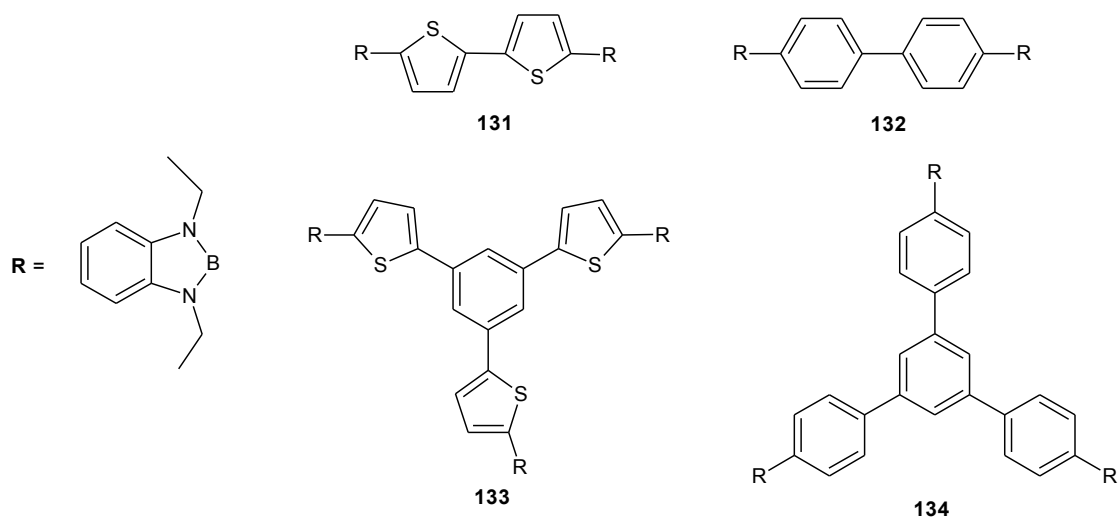
**Table 3.1:** The photophysical data of the thiophene-functionalised diazaborole compounds **128a**, **128b** and **130**.

Compound	$\lambda_{\text{max(abs)/nm(THF)}}$	$\lambda_{\text{max(emi)/nm(THF)}}$	$\Phi_{\text{F/A}}(\%)(\text{THF})$	Stokes shift (cm <sup>-1</sup> )
<b>128a</b>	296	382	-	86
<b>128b</b>	326	433	29	107
<b>130</b>	341	371	18	30

From their results (Table 3.1), Domke *et al.* concluded that the enlargement of the  $\pi$ -system at the 2-position does not only enhance the brightness ( $\Phi_{\text{F/A}} = 29\%$ ) of the emitted light but it also results in a bathochromic shift of both the absorption (from 296 nm to 326 nm) and emission maxima (from 382 nm to 433 nm). According to Domke and co-workers, the observed phenomenon was due to an increased in conjugation length which decreases the energy gap between HOMO and LUMO, thus shifting the spectra to the longer wavelengths. On the other hand, extending the  $\pi$ -system at the backbone of the diazaborole compounds resulted in a bathochromic shift of the absorption maximum (from 296 nm to 341 nm) and a hypsochromic shift of the emission maximum (from 382 nm to 371 nm).<sup>47</sup> In addition, this effect also reduces the brightness of the emitted light as reflected by a smaller quantum yield ( $\Phi_{\text{F/A}} = 18\%$ ) for compound **128a** relative to that of **128b** ( $\Phi_{\text{F/A}} = 26\%$ ). The explanation for the observed trend was, however, not provided by the authors.<sup>47</sup>

Three years later Weber and *et al.*<sup>48</sup> conducted the UV-visible spectroscopic and computational studies to examine the influence of increasing the number of benzodiazaborolyl groups on the luminescence properties of their compounds.

The desired compounds (**Figure 33**) were prepared either from 2-bromo-1,3-diethyl-1,3,2-benzodiazaborole or *N,N'*-diethyl-1,2-diaminobenzene with the corresponding lithiated-aryl halides in yields ranging from 53-91% (**Figure 33**).<sup>47,48</sup>



**Figure 33: Structures of bis- and tris-1,3,2-benzodiazaboroles**

The absorption and emission data for the synthesised bis- and tris-1,3,2-benzodiazaborole compounds are summarised in table 3.2. The photophysical data acquired by Weber and *et al.*<sup>48</sup> revealed that, increasing the number of benzodiazaborolyl groups result in a hypsochromic shift of the absorption maxima with notably longer wavelengths for bis-1,3,2-benzodiazaboroles **131** and **132** (Figure 33).<sup>48</sup>

**Table 3.2** The absorption and emission data for compounds **131-134**.

Compound	$\lambda_{\text{max(abs)}}$ /nm (THF)	$\lambda_{\text{max(emi)}}$ /nm (THF)	$\Phi_{\text{F/A}}$ (%) (THF)	Stokes shift (cm <sup>-1</sup> )	Yields%
<b>131</b>	351	448	52	6200	91
<b>132</b>	304	427	52	9500	55
<b>133</b>	330	446	33	7900	53
<b>134</b>	300	471	71	9400	58

In contrast to the absorption spectra, the emission maxima for these compounds were red shifted going from bis-1,3,2-benzodiazaboroles (**131** and **132**) to tris-1,3,2-benzodiazaborole (**133** and **134**) compounds. This trend was attributed to an increased in the length of the extended  $\pi$ -communication between benzodiazaborolyl groups for

tris-1,3,2-benzodiazaborole **131-134** compared to that of bis-1,3,2-benzodiazaborole compounds (**131** and **132**).

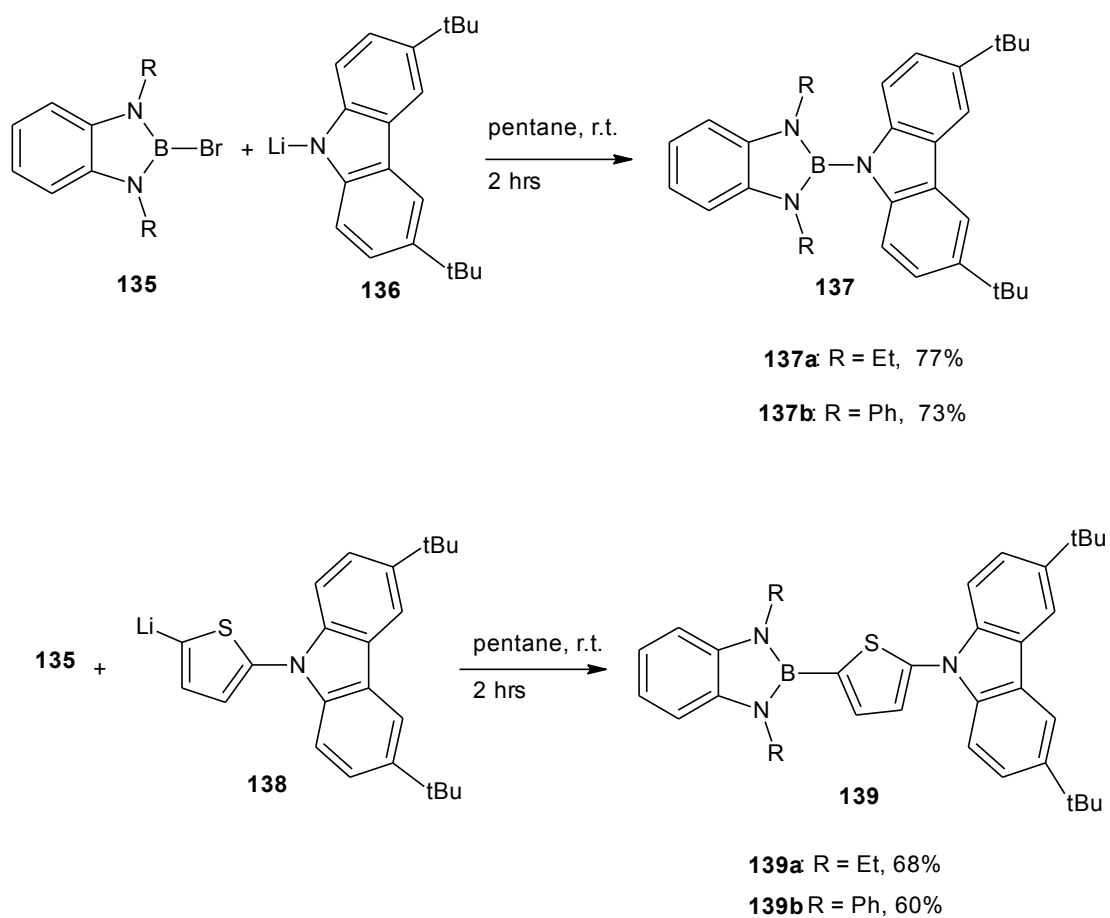
This study also showed that the thiophene systems **131** ( $\Phi = 52\%$ ,  $6200\text{ cm}^{-1}$ ) and **133** ( $\Phi = 33\%$ ,  $7900\text{ cm}^{-1}$ ) generally have smaller Stokes shifts\* as well as quantum yields compared to phenylene bridged compounds **132** ( $\Phi = 52\%$ ,  $9500\text{ cm}^{-1}$ ) and **4h** ( $\Phi = 71\%$ ,  $9400\text{ cm}^{-1}$ ). Weber *et al*<sup>48</sup> reasoned the above observation to be due to the excited singlet state,  $S_1$ , (for thiophene systems) undergoing rapid loss of energy *via* internal conversion (IC) and intersystem crossing (ISC) to the triplet state,  $T_1$ , than the benzene bridged compounds. ISC has been demonstrated elsewhere<sup>49</sup> to be facilitated by the introduction of heavy atoms such as sulphur which enhances spin-orbit coupling in the molecule.<sup>49</sup>

In 2010, Lothar and co-workers<sup>50</sup> extended their synthetic, photophysical and computational studies to carbazole and 5'-carbazolyl-2'-thienyl functionalised benzo-1,3,2-diazaborolane compounds. These studies focused on exploring the influence of incorporating both the benzodiazaborolyl group and the carbazole group within one molecule, in which the benzodiazaborolyl group is forced to act as an electron acceptor by a carbazole group. Their studies also focused on investigating the influence of introducing a bridging  $\pi$ -spacer (thiophene) between the benzodiazaborolyl group and the electron-donating carbazole group on their spectroscopic characteristics.<sup>50</sup> Lothar *et al.* reported that the desired compounds were synthesised in yields ranging from 60% to 77% from the reaction of 2-bromo-1,3-diethyl-1,3,2-benzodiazaborole (**135**) with either the lithiated carbazole (**136**) or the lithiated (2-thienyl)-carbazole (**138**) in pentane (Scheme 3.7).

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\* Stokes Shifts is the energy lost between excitation and emission via non-radiative processes such as IC and ISC. The higher the energy lost (the larger the Stokes Shifts) the greater the bathochromic shift of the emission spectra.





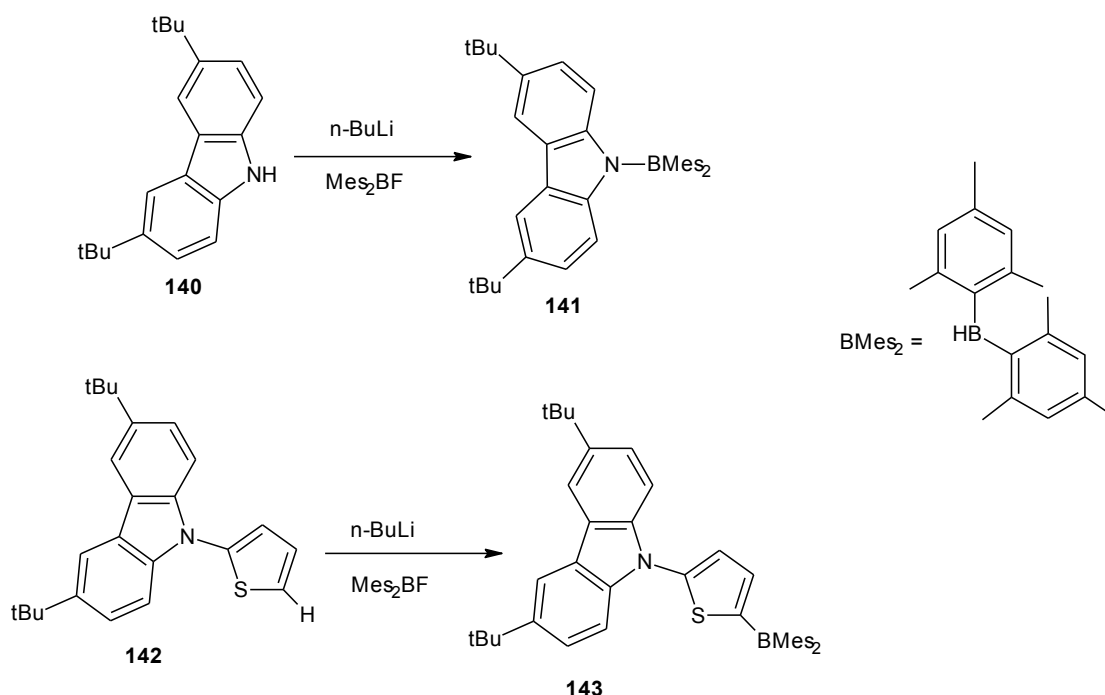
**Scheme 47**

The synthesised compounds **137a**, **137b**, **139a** and **139b** show blue luminescence with a notable brightest colour displayed by 2-carbazolyl-1,3,2-benzodiazaboroles (**137a** and **137b**). Compounds **137a** and **137b** showed absorption maxima at 296 nm and 297 nm, and the emission maxima at 348 nm and 342 nm, respectively. These compounds displayed a small Stokes shift of 700  $\text{cm}^{-1}$  which indicated the lack of  $\pi$ -communication between the benzodiazaborolyl and the carbazolyl groups. The UV/Vis spectra of compounds **139a** and **139b** displayed major bands at 296 nm. The emission spectra showed intense bands at 371 nm (**139a**) and 388 nm (**139b**). These data correspond to larger Stokes shifts of 5800  $\text{cm}^{-1}$  (**139a**) and 5000  $\text{cm}^{-1}$  (**139b**). The large Stokes shifts is consistent with the presence of a charge transfer both from the carbazolyl and benzodiazaborolyl groups to the thiophene units.

From these results, Weber *et al.*<sup>51</sup> concluded that the benzodiazaborolyl unit does not function as an electron acceptor as originally expected, but instead it functions as an

electron donor. This observation was confirmed with computational studies which revealed that the HOMO of compounds **137a** and **137b** are localised on the carbazole group, whereas, the HOMO of compounds **139a** and **139b** were mainly represented by benzodiazaborolyl unit which was initially expected to function as the LUMO. This behaviour was attributed to a weak  $\pi$ -accepting ability of benzodiazaborolyl groups.<sup>51</sup> In keeping with this, Chrostowska *et al.*<sup>52</sup> have recently (2011) designed and synthesised molecules in which benzodiazaborolyl group is replaced by a strongly  $\pi$ -accepting dimesitylborolyl moiety, and investigated their photophysical characteristics.<sup>52</sup>

The synthesis of the desired compounds **141** and **142** (Scheme 48) was effected by the lithiation of the starting materials 3,6-di-*tert*-butylcarbazole **140** and 3,6-di-*tert*-butyl-*N*-(2-thienyl)carbazole **142** with *n*-BuLi in diethyl ether.<sup>52</sup> The treatment of the resulting mixture with fluorodimesitylborane solution (Mes<sub>2</sub>BF), in THF, provided the corresponding products **141** and **143** in 70% and 66% yields, respectively (Scheme 48).<sup>52</sup>



**Scheme 48**

The photophysical data for compounds **140-143** are summarised in table 3.3. For comparison, the photophysical data for the corresponding benzodiazaborolyl functionalised compounds **137a**, **137b**, **139a** and **139b** (Scheme 48) are also included.

**Table: 3.3.** The photophysical data of compounds **137a**, **137b**, **139a**, **139b**, **141** and **143**.<sup>52</sup>

Compounds	$\lambda_{\text{max,abs}}$ (nm)	$\lambda_{\text{max,em}}$ (nm)	Stokes shift (cm <sup>-1</sup> )	$\Phi_f^c$
<b>141<sup>a</sup></b>	288	450	9000	0.15
<b>141<sup>b</sup></b>	288	492	10200	0.19
<b>143<sup>a</sup></b>	295	441	6100	0.70
<b>143<sup>b</sup></b>	295	465	3300	0.43
<b>137a<sup>a</sup></b>	297	452	500	0.37
<b>137a<sup>b</sup></b>	296	349	700	0.37
<b>137b<sup>a</sup></b>	296	349	700	0.44
<b>137b<sup>b</sup></b>	296	344	800	0.33
<b>139a<sup>a</sup></b>	296	372	3600	0.40
<b>139a<sup>b</sup></b>	297	379	5800	0.21
<b>139b<sup>a</sup></b>	296	395	6300	0.21
<b>139b<sup>b</sup></b>	297	396	5000	0.15
<sup>a</sup> In cyclohexane. <sup>b</sup> In CH <sub>2</sub> Cl <sub>2</sub> . <sup>c</sup> against standard POPOP <sup>a</sup> ( $\Phi = 0.93$ )				

From this study, Chrostowska *et al.*<sup>52</sup> documented that the UV/Vis spectra of all the compounds (in cyclohexane) show strong absorption bands in the narrow range 288-297 nm. The positions of these bands are virtually unaffected by changing the polarity of the solvents used which points to the absence of solvatochromism and the low dipole moments of the compounds in the ground state (Table 3.3). Similar to UV/Vis spectra, the quantum yields of these compounds do not differ significantly owing to the high probability of non-radiative decay processes (Table 3.3). These observations suggest that the electronic transition only occurs within the carbazole fragment with no participation of the benzodiazaborolyl moiety, which clearly indicates that the benzodiazaborolyl part of the molecule does not have any significant influence in the electronic transition in the ground state. Unlike the UV/Vis spectra, the luminescence spectra of these compounds differ significantly. The emission spectra of dimesitylborolyl functionalised compounds (**141** and **143**) show intense bands in

<sup>a</sup> POPOP stands for 5-Phenyl-2-[4-(5-phenyl-1,3-oxazol-2-yl)phenyl]-1,3-oxazole

cyclohexane at 450 nm (Stokes shift = 9000 cm<sup>-1</sup>) and 441 nm (Stokes shift = 6100 cm<sup>-1</sup>), respectively.<sup>52</sup> These bands exhibit bathochromic shift (in DCM) to 492 nm (10200 cm<sup>-1</sup>, **141**) and 465 nm (6100 cm<sup>-1</sup>, **143**) with increasing the solvent polarity which reflect positive solvatochromism. According to Chrostowska and co-workers,<sup>52</sup> the presence of solvatochromism and the large Stokes shifts displayed by these compounds are suggestive of a more polar excited state (larger dipole moments) as a results of intramolecular charge transfer. This observation clearly differs with the photophysical findings of the benzodiazaborolyl functionalised compounds **137a** and **137b** which displayed Stokes Shifts of only 500-800 cm<sup>-1</sup> and the absence of solvatochromism.

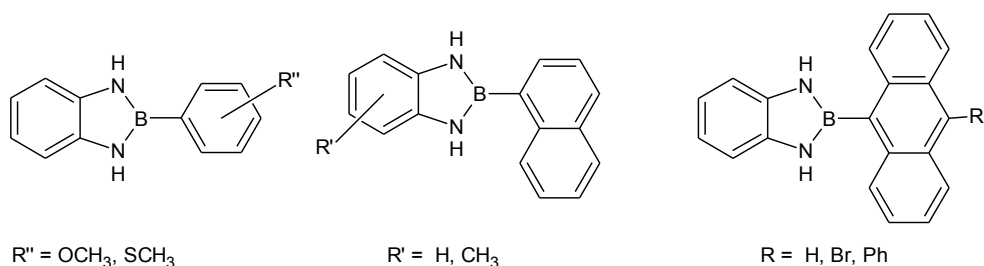
In contrast to **137a** and **137b**, compounds **139a** and **139b** show unexpectedly high Stokes shifts. This was attributed to higher planarity of compounds **139a** and **139b** and the shorter B-C bond which increases  $\pi$ -communication and the orbital overlap between  $2p_z$  orbital on the boron atom and the attached  $\pi$ -organic scaffold as reported by the authors.

From these studies, Chrostowska and co-workers,<sup>52</sup> concluded that, the benzodiazaborolyl group does not function as a  $\pi$ -electron-donating group as vastly documented in the literature, but instead it functions as a  $\pi$ -electron-accepting group. Thus, the replacement of the benzodiazaborolyl group with an electron-poor dimesitylborolyl substituent significantly alters the nature of frontier orbitals. Unlike in the benzodiazaborolyl functionalised carbazole compounds in which both the HOMO and LUMO are localised in the carbazolyl group, the HOMO of the dimesitylborolyl functionalised carbazole compounds is mainly located on the carbazolyl group whereas the LUMO is localised on the benzodiazaborolyl unit as initially expected.<sup>52</sup>

## Aims of Chapter Three

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This study is aimed at investigating the synthesis of a range of 2-arylbenzo-1,3,2-dizaborole compounds (**Figure 34**) which will then be fully characterised using spectroscopic techniques including  $^1\text{H}$  and  $^{13}\text{C}$  nuclear magnetic resonance, infra red and high resolution mass spectrometry.



**Figure 34**

The second part of this study is focused on investigating the electronic structures of the synthesised compounds by acquiring and studying their:

- i. UV/Visible absorption spectra
- ii. Luminescence (emission) spectra

This section will be followed by DFT calculations of the synthesised compounds which are expected to shed light on the nature of frontier orbital, the electronic transition within the molecules and the energies associated with each electronic transition.

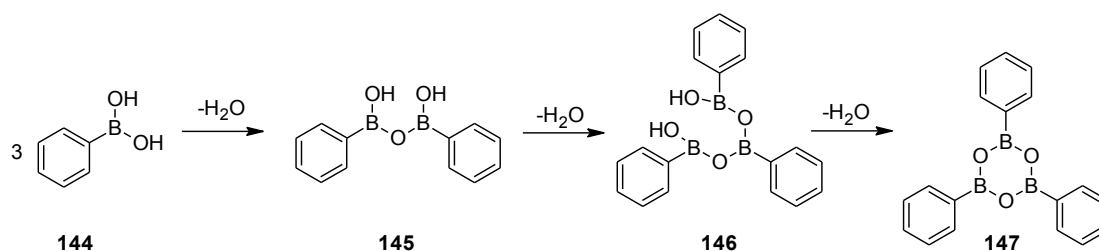
# Results and Discussion

## Synthetic Studies

### 3.3 Synthesis of Arylboronic acids

The widespread applications of arylboronic acids as synthetic intermediates have demanded the development of new methods for the preparation of such compounds. As consequence, there have been several procedures in literature that describe the preparation of such compounds. However, the metal-halogen exchange method, which was first developed by Johnson and co-workers in the early 1930s,<sup>53</sup> is by far the most economical and reliable method for the preparation of arylboronic acids in good yields. For this reason, the magnesium-halogen exchange strategy was chosen for the synthesis of our desired arylboronic acids in this project.

Johnson and co-worker<sup>53</sup> reported that most boronic acids exist as mixtures of cyclic and linear oligomeric anhydrides and boraxines upon slow dehydration. This process makes the isolation and characterisation of free boronic acids a challenging task. For example, the isolation and characterisation of **144** is complicated by the presence of oligomeric ahydrides derivatives **145**, **146** and **147** (Scheme 49).



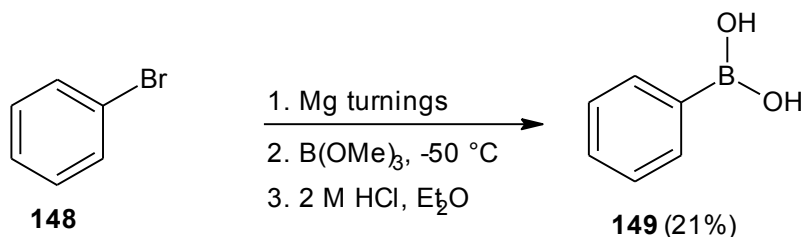
**Scheme 49**

For this reason, most boronic acid provide unreliable melting points, as well as complex mass and NMR spectra. As a consequence, most boronic acids are transformed into their corresponding boronic esters for accurate analysis and characterisation. Based on these facts, the arylboronic acids synthesised in this project will not be fully characterised using  $^1H$  and  $^{13}C$  NMR techniques; however, they will be converted to their corresponding benzodiazaborole derivatives which will then be fully characterised. This approach is consistent with literature reports.<sup>14</sup> The following

section describes the synthesis of arylboronic acids from their corresponding aryl halides

### 3.3.1 Synthesis of phenylboronic acid (**149**)

The first attempt to synthesise phenylboronic acid (**149**), following the procedure reported by Johnson and co-workers afforded the desired product as a white solid in only 21% isolated yields (**Scheme 50**).



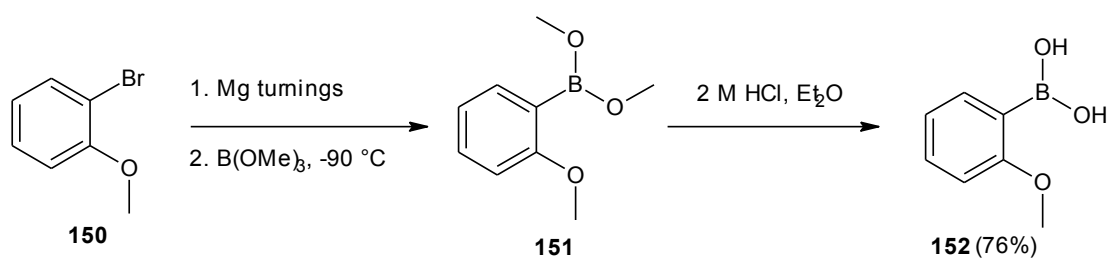
**Scheme 50**

The low yields obtained for phenylboronic acid was attributed to the formation of di- and trisubstituted boron containing by-products as reflected by the <sup>11</sup>B NMR spectrum. To solve this problem, Diorazio *et al.*<sup>54</sup> reported that lowering the temperature to or below -78 °C dramatically reduces the formation of the unwanted products. To test the hypothesis proposed by Diorazio *et al.*,<sup>54</sup> the above reaction was repeated at -90 °C<sup>†</sup>. The hydrolysis step afforded the desired crude product as a white solid, which when recrystallised in boiling water afforded the title compound in 86% as colourless needle-like crystals. The melting point (215-217 °C) of the product was found to be well within the reported range of (lit.<sup>55</sup> 213-217 °C). The infra red spectrum of the product confirmed the presence of the hydroxyl group as evident with a broad absorption band resonating at 3239 cm<sup>-1</sup> and a sharp band at 1346 cm<sup>-1</sup> ascribed to the B-O stretching frequency.

### 3.3.2 Synthesis of 2-methoxyphenylboronic acid (**152**)

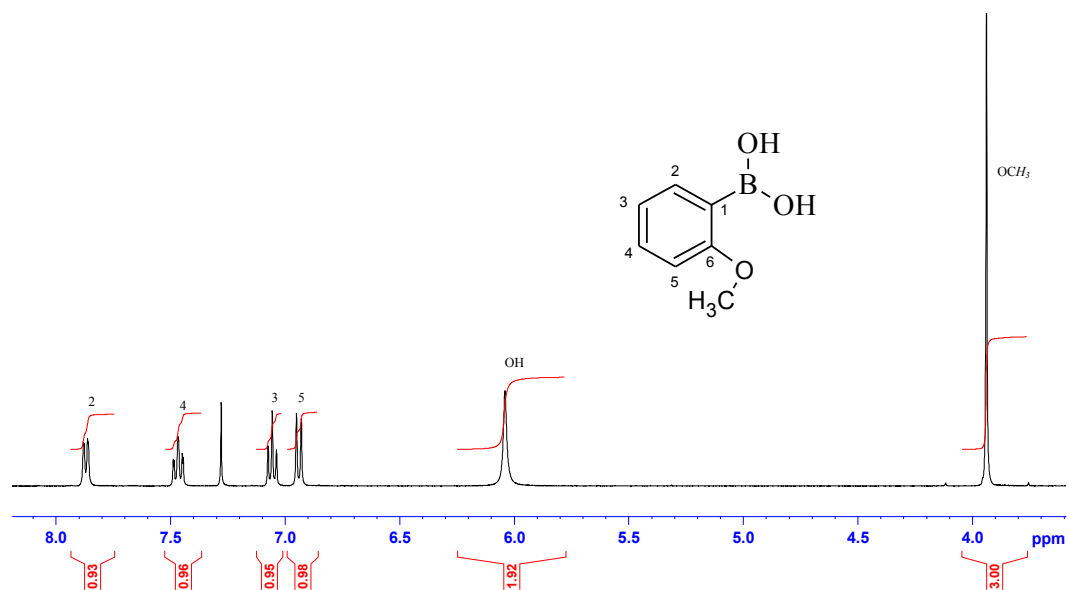
With the optimised reaction condition in hand, several other aryl bromides were converted into their corresponding boronic acids in moderate to good yields. 2-Methoxyphenylboronic acid (**152**) was synthesised in 76% yield from 2-bromoanisole (**150**) according to the above mentioned optimal reaction conditions (**Scheme 51**).

<sup>†</sup> The cooling system used was a mixture of toluene and liquid nitrogen.



**Scheme 51**

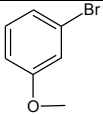
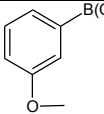
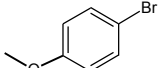
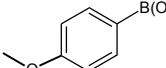
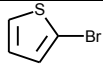
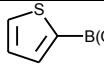
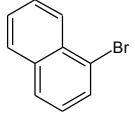
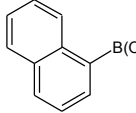
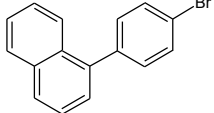
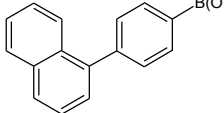
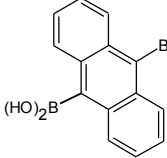
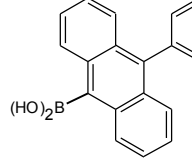
Recrystallisation of the resulting white solid, after the dilute acid hydrolysis step, afforded the desired compound **152** as colourless needle-like crystals. The  $^{11}\text{B}$  NMR spectrum showed a single signal at 29.3 ppm which is attributed to the expected product and its chemical shift is well within the reported range.<sup>56</sup> The  $^1\text{H}$  NMR spectrum of **152** revealed the product to be pure and its peak assignments are depicted in **Figure 35** below. The synthesis of other aryl boronic acids required for this study was carried out following the general procedure used for the synthesis of 2-methoxyphenyl boronic acid (**152**) (Table 3.4).



**Figure 35:  $^1\text{H}$  NMR spectra for 2-methoxyphenyl boronic acid**



**Table 3.4. Summary of polyaryl boronic acids synthesised.**

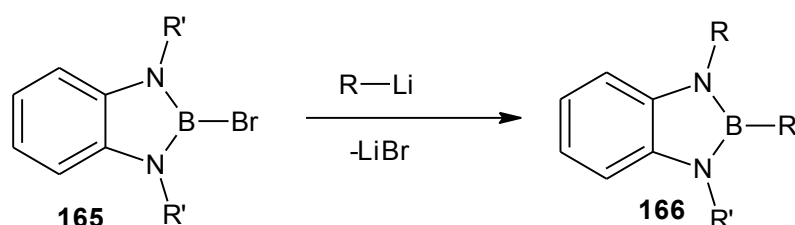
Entry	ArBr	product	Yield (%)	Mp °C (literature °C)
1	 154	 154	76	165-167 (165-166)
2	 155	 156	Not isolated	N/A
3	 157	 158	79	138-140 (138-140)
4	 159	 160	90	175-178 (177-178)
5	 161	 162	58	183-185
6	 163	 164	49	171-172

### 3.4 Synthesis of 1,3,2-benzodiazaborole

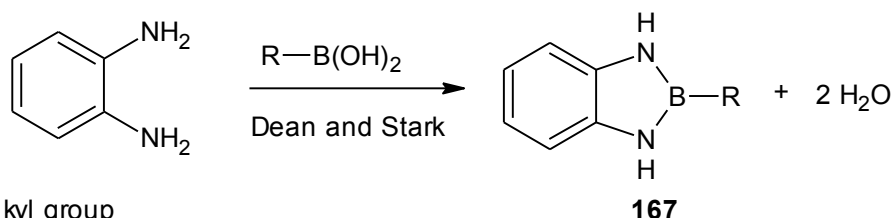
The chemistry of conjugated molecules, metal complexes and polymers functionalised with triarylborane moiety has attracted a lot of interest and has been the subject of consideration in the past decade. These compounds have shown intriguing optical and electronic properties which are suggestive of potential applications in electronic devices. Logically, a lot of attention has been concentrated on the synthetic studies of these compounds in order to develop new and efficient methods for their preparation.<sup>58</sup>

As a consequence, numerous procedures to access three-coordinate boron compounds are now available. However, there are two distinct methods mostly used for the preparation of 1,3,2-benzodiazaborole compounds. Method A involves the *in situ* lithiation of arylhalide/arenes with butyllithium solution. The lithiated intermediate is then quickly quenched with 1,3,2-benzodiazaborolyl bromide solution affording the desired compound in moderate to good yields. This method is, however, only limited to substrates bearing organolithium insensitive substituents and it also requires scrupulously inert conditions as lithiated intermediates are highly air and moisture sensitive.<sup>58</sup>

#### Method A



#### Method B



$R'$  = any alkyl group

$R$  = any unsaturated hydrocarbon

#### Scheme 52

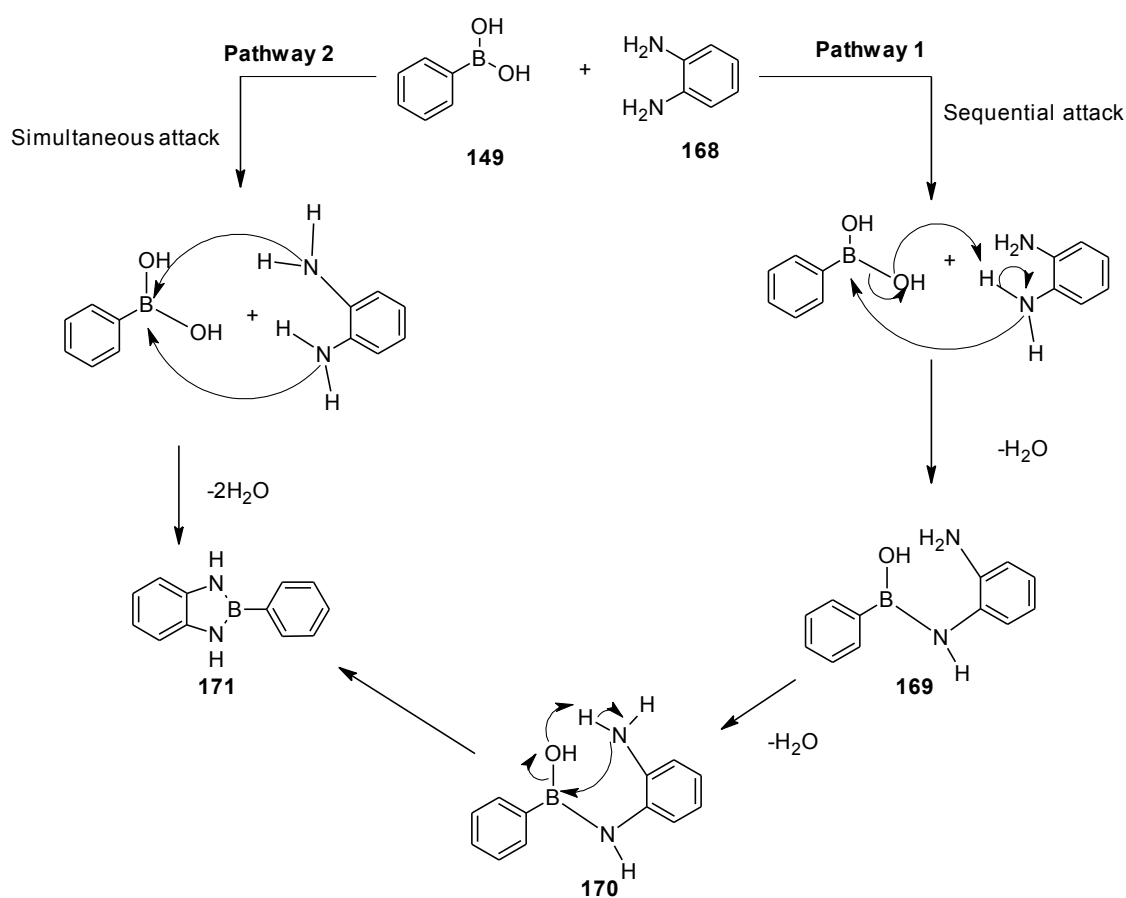
Method B involves heating (under reflux) the corresponding boronic acid and 1,2-diamino derivatives in toluene using a Dean-Stark conditions (Scheme 53). The

desired product is formed from the cyclocondensation of the two starting materials with the elimination of two water molecules. Unlike method A, this method is insensitive of any functional group and does not require inert condition as water is the by-product of the reaction. In addition, when 1:1 stoichiometric ratio of the starting materials are used, the purification of the desired compounds is not required as the desired products tend to precipitate out of solution upon cooling.<sup>58</sup> For these reasons, method B was chosen for the preparation of 1,3,2-benzodiazaborole compounds in this project.

In the following discussion, the mechanistic investigation for the formation of 1,3,2-benzodiazaborole compounds conducted by Soloway and co-worker will be discussed. This section will be followed by the synthesis of a range of 1,3,2-benzodiazaborole compounds we conducted in this project. Spectroscopic techniques will be included and discussed to confirm the successful synthesis, the purity and structures of our compounds.

### 3.4.1 Mechanism of the formation of 1,3,2-benzodiazaborole compounds

Soloway and co-worker<sup>59</sup> were the first to propose the mechanism for the formation of 1,3,2-benzodiazaborolyl-functionalised compounds. According to the authors, the mechanism involves cyclocondensation of boronic acid with 1,2-diamino derivatives *via* the elimination of two water molecules. This process is believed to proceed *via* the nucleophilic attack of the central electron-deficient boron atom by the electron rich diamino groups. However, it is unclear whether this process proceeds through (i) a sequential attack (**pathway 1**), whereby one amino group first attacks the boron atom to form intermediate **A** (**Scheme 53**). This step is then followed by cyclocondensation whereby boron atom is attacked by free amino group resulting in the elimination of the second water molecule, or whether it proceeds through (ii) simultaneous attack (**pathway 2**) whereby both amino groups simultaneously attack the boron atom affording the final product **171** directly.<sup>59</sup>



Scheme 53

To proof their hypothesis, the authors reacted phenyl boronic acid (**149**) with 1,2-diaminobenzene (**168**) in refluxing methanol. After a short while, the evaporation of methanol afforded a low melting solid whose infrared spectrum still showed the presence of a primary amino and hydroxyl stretching bands. The infrared spectrum also showed a new sharp absorption band resonating in the range of 1125-1115  $\text{cm}^{-1}$  which was assigned to the formation of a new B–N bond having a single bond character.<sup>59</sup>

When the low melting point solid was heated and subsequently re-analysed, the infrared spectrum of a new product showed the absence of both the primary amino and hydroxyl stretching bands indicative of full conversion of the starting material to product **171**. The spectrum also showed two distinct absorption bands at 3482 and 1378  $\text{cm}^{-1}$  which were assigned to the secondary amine stretching frequency and a B–N bond stretching frequency exhibiting a partial double bond character, respectively.<sup>59</sup>

In order to interpret their finding, the authors compared both pathways and correlated their results to the experimental findings. According to the authors, if the mechanism proceeds *via* pathway 2, the low melting solid obtained initially would be compound **171**. However, the presence of the absorption bands assignable to the stretching frequencies of free amino and hydroxyl groups in the infrared spectrum of the isolated intermediate clearly indicated that the intermediate was not compounds **171** (since this compound does not have any free hydroxyl and amino groups), this realisation automatically ruled out pathway 2.<sup>59</sup>

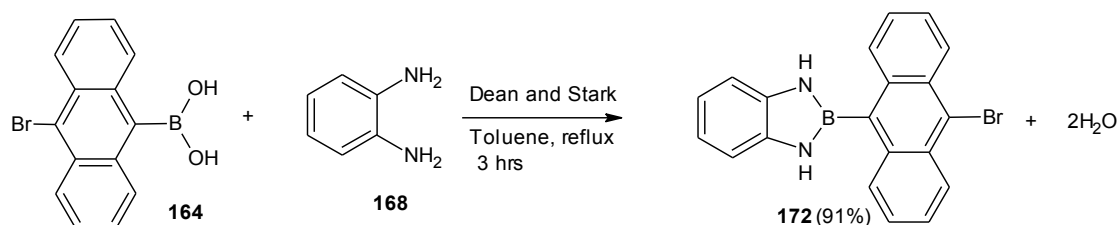
Alternatively if the mechanism proceeds *via* pathway 1, the low melting point intermediate would have been compound **A**. The appearance of a new absorption band with a characteristic frequency of 1125-1115  $\text{cm}^{-1}$  indicated the formation of only one B–N bond with a single bond character. The presence of both amino and hydroxyl stretching bands further supported that the intermediate isolated was **A**. The authors therefore concluded that the formation of 1,3,2-benzodiazaborole compounds follow pathway 1.<sup>59</sup> The following section discusses the synthesis of a range of arylbenzo-1,3,2-diazaborole compounds using method **B** as described above.

### 3.4.2 SYNTHESIS OF 2-ARYLBENZO-1,3,2-DIAZABOROLES

With aryl boronic acids in hand, a number of 2-arylbenzo-1,3,2-diazaborole compounds were synthesised from the condensation of the corresponding aryl boronic acid with 1,2-diaminobenzene (**Scheme 54**). Below is the representative procedure for the synthesis of 2-arylbenzo-1,3,2-diazaborole compounds. Table 3.4 summarises the 2-arylbenzo-1,3,2-diazaborole compounds synthesised.

#### 3.4.2.1 Synthesis of 2-(10-bromo-9-anthryl)benzo-1,3,2-diazaborole (**172**)

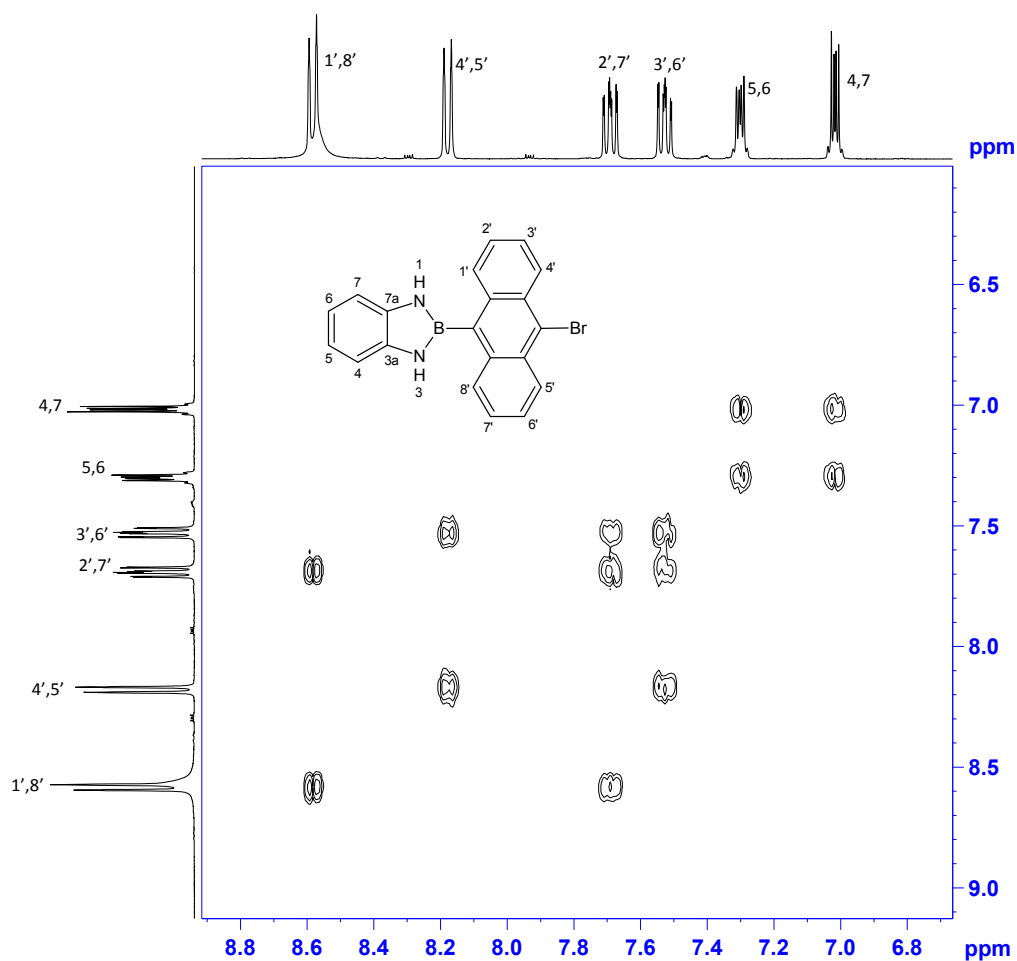
10-Bromoanthryl-9-boronic acid (**164**) was reacted with 1,2-diaminobenzene (**168**) in refluxing toluene to afford 2-(10-bromo-9-anthryl)-benzo-1,3,2-diazaborole (**172**) as yellow powder (**Scheme 54**).



**Scheme 54**

The <sup>1</sup>H and <sup>13</sup>C NMR spectra of **172** revealed that the yellow powder obtained was indeed the expected product and was relatively clean with integral ratios and carbon signals corresponding exactly to the expected number of proton and carbons, respectively. The COSY spectrum of the title compound revealed a broad peak in the region δ 8.53-8.62 ppm which was assigned to the two *N-H* functionalities (Figure 3.17a). The doublet appearing in the same range (δ 8.53-8.62 ppm) with *J* = 8.6 Hz is coupled to one of the protons whose multiplet is resonating in the range δ 7.66-7.73 ppm. Because the title compound is symmetrical along the x-axis, the protons on the first and the third aromatic ring of the anthryl moiety are therefore expected to be identical. For this reason, the doublet at δ 8.53-8.62 ppm was assigned to protons 1' and 8' and these protons were found, according to the COSY spectrum, to be coupled to 2'-H and 7'-H. The doublet resonating at δ 8.15-8.21 ppm is also slightly deshielded and was found to be coupled to the protons whose multiplet appears in the range δ 7.49-7.56 ppm, these signals were assigned to protons 4'-H, 5'-H and 3-H,6'-

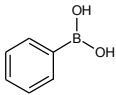
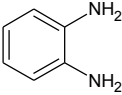
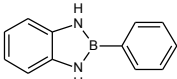
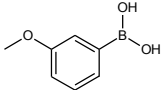
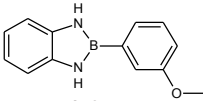
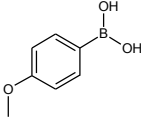
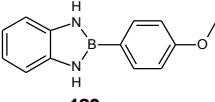
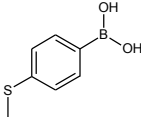
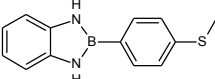

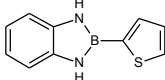
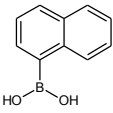
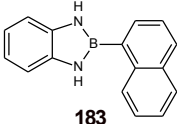
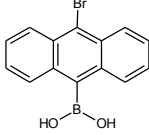
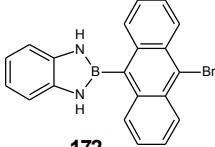
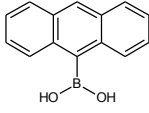
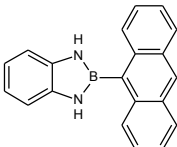
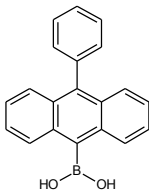
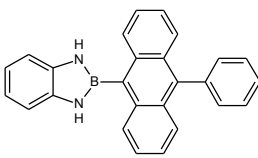
H, respectively. The protons on the benzodiazaborolyl group are similar for most of these compounds, and were assigned accordingly. The  $^{13}\text{C}$  NMR showed ten carbon peaks whose assignments were done according to figure 47.



**Figure 36: COSY spectrum for compound 172**

## 3.5 Summary of Synthetic Studies

**Table 3.4:** Summary of synthesised 2-arylbenzodiazaborole compounds

Entry	Boronic acid	diamine	product	Yields (%)
1		 <b>168</b>	 <b>173</b>	93
2		<b>168</b>	 <b>179</b>	89
3		<b>168</b>	 <b>180</b>	85
4		<b>168</b>	 <b>181</b>	89
5		<b>168</b>	 <b>182</b>	91
6		<b>168</b>	 <b>183</b>	81
7		<b>168</b>	 <b>172</b>	91
8		<b>168</b>	 <b>184</b>	52
9		<b>168</b>	 <b>185</b>	43



# **Spectroscopic Studies**

## **3.6 UV/Vis and Luminescence Studies**

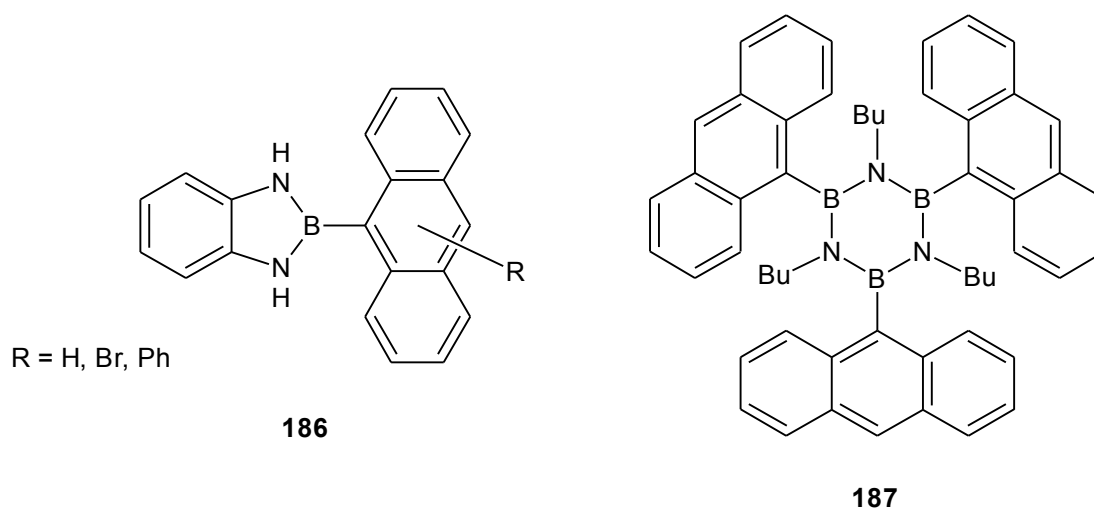
### **Preface**

The chemistry of 1,3,2-benzodiazaborolyl-functionalised organic compounds has experienced rapid development in the last decade.<sup>58,61</sup> These compounds are electron poor and are considered as strong  $\pi$ -electron acceptors owing to their vacant  $2p_z$ -orbital on the central boron atom. The vacant  $2p_z$ -orbital has, on many occasions, been proven to be capable of significant delocalisation with  $\pi$ -orbitals of the attached organic system. This delocalisation has been reported to stabilise the LUMO of the attached organic  $\pi$ -system and thus facilitating  $\pi$ -communication between the 1,3,2-benzodiazaborolyl-group and the adjacent  $\pi$ -electron system. This process is accompanied by a change in the HOMO-LUMO energy gap of the molecule, which has been reported to be responsible for the intriguing absorption and emission characteristics revealed by these compounds.<sup>58,61</sup>

It has been reported that the HOMO-LUMO energy gap of these molecule (so are their absorption and emission properties) could principally be adjusted by changing the structure of the compound. Yamaguchi *et al.*<sup>62</sup> showed that the donor functionalities (SMe and NMe<sub>2</sub>) are advantageous for the optical properties of oligophenyl-ethynylene compounds.<sup>62</sup> More recently, Weber *et al.*<sup>48</sup> have synthesised and studied the chemical and physicochemical properties of 1,3,2-benzodiazaboroles functionalised with arenes, biphenyls, thiophenes and dithiophenes. These compounds were reported to display bright blue luminescence with higher Stoke shifts and quantum yields.<sup>48</sup>

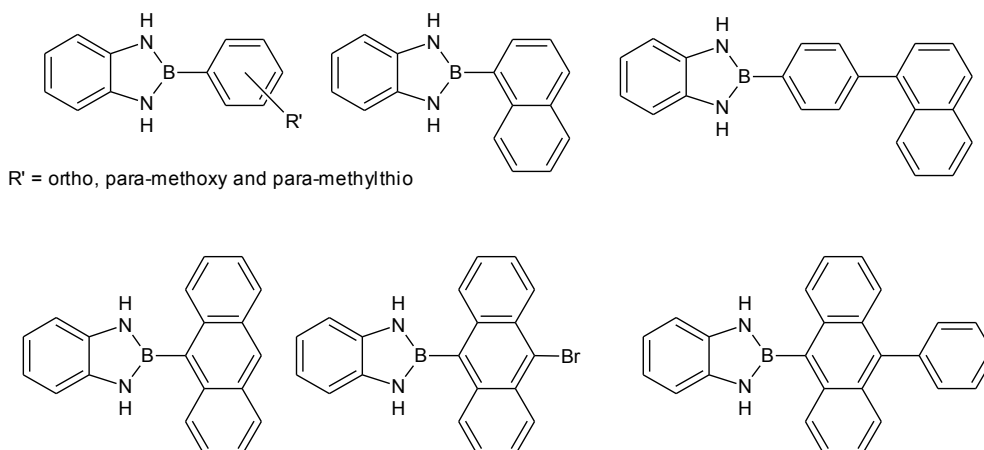
Anthracene and its derivatives are well known compounds for displaying violet-blue luminescence in most organic solvents when irradiated with ultra violet light.<sup>63</sup> Based on these intriguing photophysical properties, these compounds have been widely used as photoluminescent compounds for OLED-based devices.<sup>64</sup> Although many anthracene-functionalised compounds have been synthesised and investigated for use in OLEDs, the search for new luminescent organic compounds that exhibit excellent photoluminescent characteristics is still urgently and highly desirable in this area.<sup>65</sup>

Despite their intriguing properties, there are only few researchers who have devoted their focus towards expanding the scope of anthryl functionalised derivatives that could be used as luminescent organic compounds.<sup>23,66</sup> Alternatively, 1,3,2-benzodiazaborole compounds functionalised with  $\pi$ -systems on the 2-position have, more recently, received considerable attention due to their interesting absorption and emission properties.<sup>48,51,58</sup> Despite the popularity of anthryl and 1,3,2-benzodiazaborole derivatives in this area, to the best of our knowledge, the design, synthetic, photophysical and theoretical studies of compounds which contain both the 1,3,2-benzodiazaborole and anthryl moieties in one molecule (**Figure 37**), compound **195**, have never been conducted to date. We are well aware of the report by Wakamiya *et al.* which details the photophysical and theoretical of related trianthryl borazine compounds (**186**), this compound is totally different from our compounds, as it contains an alternating boron–nitrogen atoms which form a six-membered ring where as our compounds form a five-membered ring (**Figure 37**).<sup>66</sup>



**Figure 37: Structures of trianthryl borazine**

With the above ideas in mind, attention was concentrated on the synthetic, photophysical, theoretical, solvatochromism, fluorescence quenching and Lewis base sensing studies of 1,3,2-benzodiazaborole compounds functionalised with phenyl, *meta* and *para*-methoxy substituted phenyl, *para*-methythio substituted phenyl, naphthyl, 10-bromo-9-anthryl and anthryl groups (**Figure 38**).



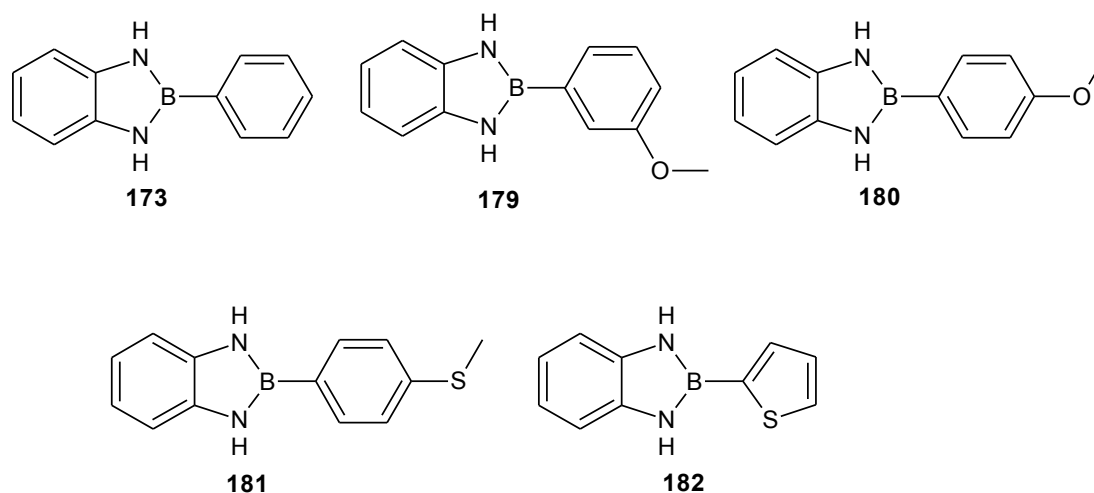
**Figure 38: Structures of 2-arylbenzo-1,3,2-diazaboroles**

In the following sections, the Uv/vis absorption and emission data for the synthesised 2-arylbenzo-1,3,2-diazaborole compounds will be discussed in order to investigate the influence of different substituents, extending  $\pi$ -conjugation length and the effect of increasing solvent polarity on the photophysical properties of these compounds. Computational studies are also discussed in order to explain the observed trends.

It is well documented in the literature that 1,3,2- benzodiazaborolyl groups function as  $\pi$ -acceptor despite their empty  $2p_z$ -orbital on the central boron atom. As a consequence, these studies are expected to shed light on the nature of frontier orbitals, which in turn are to reveal the role of 1,3,2-benzodiazaborolyl group in our compounds. In the following discussion, compound **173** will be treated as a standard compound, that is, all the spectroscopic comparisons will be made relative to the data of this compound (**Figure 38**).

### 3.6.1 The effect of donor substituents (OMe and SMe)

#### 3.6.1.1 UV-Vis Absorption Spectroscopy of Compounds 178, 180, 181, 183 and 184



**Figure 39: Compounds 173, 179, 180, 181 and 182**

The UV/vis absorption maxima for compound **173**, **179**, **180**, **181** and **182**, in different solvents, are summarised in Table 3.5 below. Since compound **173** serve as a reference compound for all the spectroscopic studies, it is therefore of great significance to fully discuss the spectral data of this compound in order to better understand the data.

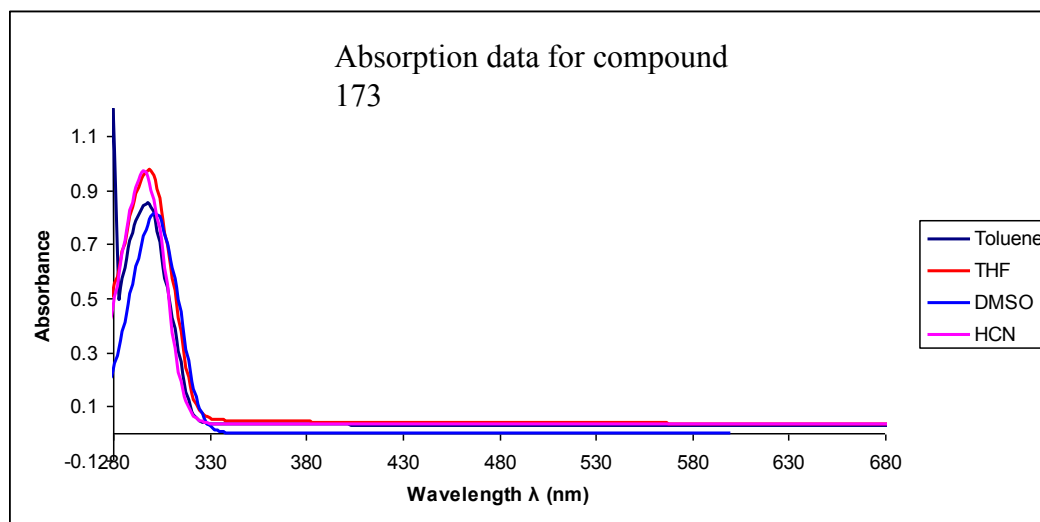
The Uv/vis spectra of **173** in toluene is dominated by a strong band at  $\lambda = 300$  nm. This band is slightly shifted to  $\lambda = 303$  nm in a more polar DMSO solvent (**Figure 40**). The small change in the absorption maxima ( $\Delta\lambda = 3$  nm) in going from a non-polar solvent (toluene) to a polar solvent (DMSO) points to the absence of solvatochromism<sup>†,4</sup>. The absences of solovatochromism in the ground state suggest that, there was no change in geometry and charge distribution during the excitation

<sup>†</sup> Solvatochromism is the change in the position of the absorption and emission spectra with change in the polarity of the solvent. These changes are a result of physical intermolecular solute-solvent interaction forces which changes the dipole moment of the molecule. Positive solvetochromism is the bathochromic shift of the spectrum as the solvent polarity increases, which points to larger dipole moment (more dipolar excited state). Negative solvetochromism is the opposite behaviour (i.e. hypsochromic shift)<sup>67</sup>.

process. Large change in the charge distribution during the excitation leads to a change in the value and the direction of dipole moment of a compound, which in turn, results in the change in the spectral position in response to the environmental changes (such as the polarity of the solvents).<sup>68,69</sup>

**Table 3.5:** Experimental absorption data for compounds **173**, **179**, **180**, **181** and **182** collected at 22° C in the concentration ranging from  $1.0 \times 10^{-6}$  to  $1.0 \times 10^{-5}$  M.

Compound	Toluene (nm)	THF (nm)	DCM (nm)	MeCN (nm)	DMSO (nm)
<b>173</b>	300	301	300	297	303
<b>179</b>	301	302	300	300	305
<b>180</b>	298	299	296	297	300
<b>181</b>	302	303	302	302	305
<b>182</b>	308	308	306	305	307



**Figure 40: Absorption spectra for compound 173 in various solvents.**

The absence of solvatochromism in the spectra of **173** is suggestive of a small dipole moment in the ground state ( $\mu_g$ )<sup>b</sup>. This observation was confirmed by computational calculation which revealed the dipole moment of  $\mu_g = 1.083$  D. Table 3.5 list selected absorption data for the above mentioned compounds, all of which exhibit intense violet-blue luminescence under UV radiation. From the table, it can be seen that the

<sup>b</sup> Calculation were performed in gas phase at B3LYP/6-311G (\*\*) level of theory.

UV/vis absorption spectra of these compounds are mainly dominated by the absorption bands with wavelength maxima in a close range 298-308 nm. The absorption maxima of these compounds are in good agreement with the computational data which also revealed the absorption maxima to be in a narrow range 287-312 nm (table 3.6).

In order to investigate the influence of the electron-donor substitutes (OMe and SMe), on the photophysical properties of these compounds, their optical and theoretical data were compared. The position of these absorption bands are virtually the same irrespective of the nature and polarity of the solvent used. These observations are consistent with the absence of solvatochromism, which in turn, point to low dipole moments in the ground state. In line with theoretical calculation, the absorption bands exhibited by these compounds are assigned to the transition from the HOMO into the LUMO with an oscillator strength ( $f$ )\* in a close range (0.42-0.73eV) and low dipole moments (1.0833-2.4773D) (Table 3.6).

**Table 3.6:** DT-DFT [B3LYP/6-311G(\*\*)] gas phase calculated absorption data for compounds **173**, **179**, **180**, **181** and **182**

Compound	$\lambda_{\text{obs}}(\text{nm})^{\text{a}}$	$\lambda_{\text{calc}}(\text{nm})$	$\mu_{\text{g}}(\text{D})$	$f(\text{eV})$	Orbital
<b>173</b>	297	287	1.0833	0.43	HOMO→LUMO
<b>179</b>	300	287	2.4773	0.44	HOMO→LUMO
<b>180</b>	297	283	2.2390	0.56	HOMO→LUMO
<b>181</b>	302	299	1.7688	0.73	HOMO→LUMO
<b>182</b>	305	312	1.4049	0.42	HOMO→LUMO
<sup>a</sup> Data collected in MeCN.					

From the table above, it is clear that the photophysical data for compounds **179**, **180**, **181** and **182** are similar to the absorption data for the standard compound **173**. The similarity in the spectroscopic data for these compounds clearly indicates that, the electron-donor functionalities (OMe and SMe) do not have any significant influence on the electronic properties of these compounds in the ground state.

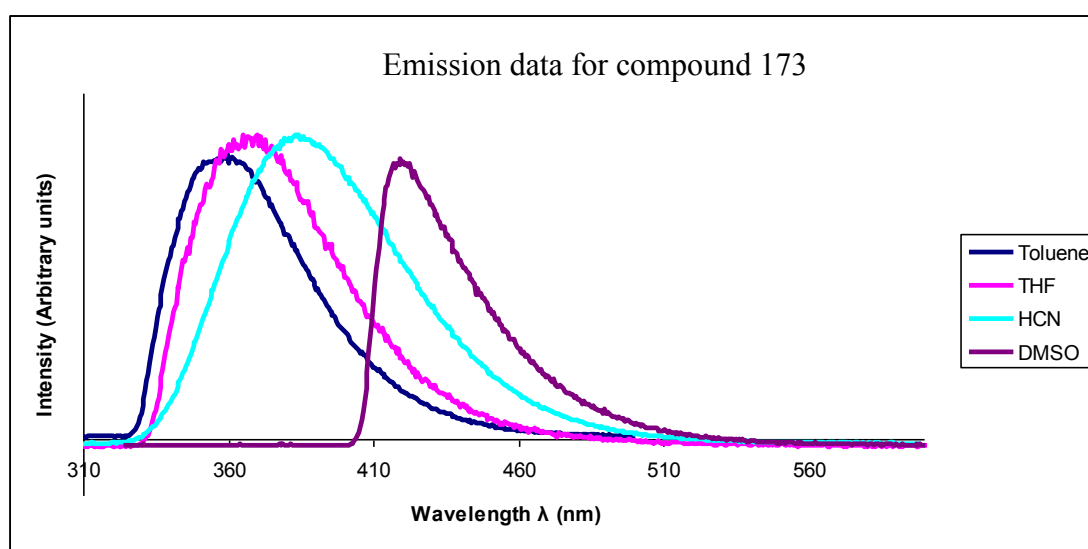
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\* Oscillator strength is the probability of the electronic transition occurring in the specified orbitals. the higher the value of  $f$  the higher the probability.

### 3.6.1.2 Emission Spectroscopy of Compounds 173, 179, 180, 181 and 182

The emission spectra of compound **173**, in different solvents, are characterised by strong bands in the range 360-422 nm in going from a non-polar toluene to a more polar DMSO, respectively (Figure 3.24). In contrast with its photophysical behaviour in the ground state, the excited state for compound **173** revealed the presence of solvatochromism. The emission bands of this compound are bathochromically shifted with increasing the polarity of the solvent. A strong band observed at  $\lambda = 360$  nm (Stoke shift =  $5600\text{ cm}^{-1}$ ) in toluene, is red shifted to  $\lambda = 368$  nm (Stoke shift =  $6000\text{ cm}^{-1}$ ),  $379$  nm (Stoke shift =  $6900\text{ cm}^{-1}$ ),  $387$  nm (Stoke shift =  $7800\text{ cm}^{-1}$ ) and  $422$  nm (Stoke shift =  $9300\text{ cm}^{-1}$ ) in THF, DCM, HCN and DMSO, respectively (**Figure 41**).

The large Stokes shift and positive solvatochromism exhibited by compound **173** are diagnostic of a more polar excited state (i.e. large dipole moment) of this compound.<sup>52</sup> The gradual increase in the Stokes Shifts with increasing the solvent polarity points to the stabilisation of the polar excited state with polar solvent. It is a matter of common knowledge that, a polar excited state is more stabilised by a polar solvent than a non-polar solvent, hence the increase in the Stokes Shifts in going from toluene to DMSO.<sup>52</sup>



**Figure 41: Emission spectra for compound 173 in various solvents.**

In the section that follows, we will compare and discuss the emission spectra of the compounds under investigation (**Figure 39**) in order to investigate the influence of

donor substituents (OMe and SMe) on the emission characteristics of these compounds. Table 3.7 lists the emission maxima for compounds **173**, **179**, **180**, **181** and **182** in different solvents. Similar to the fluorescence spectrum of **173**, the emission spectra of the other compounds show intense fluorescence bands in the range *ca* 355 nm to *ca* 423 nm in going from toluene to DMSO, respectively (Table 3.7).

**Table 3.7** Emission data for compounds **173**, **179**, **180**, **181** and **182** collected at 22° C in the concentration ranging from  $1.0 \times 10^{-6}$  to  $1.0 \times 10^{-5}$  M.

Compound	Toluene (nm)	THF (nm)	DCM (nm)	MeCN (nm)	DMSO (nm)
<b>173</b>	360	368	379	387	422
<b>179</b>	363	369	383	390	422
<b>180</b>	355	350	358	366	330
<b>181</b>	379	389	403	405	423
<b>182</b>	371	391	401	407	418

The bathochromic shifts of the emission maxima of these compounds, with increasing the polarity of the solvent, indicate the presence of significant positive solvatochromism, which in turn, points to the change in the charge distribution (i.e. the presence of a polar excited state) of these molecules in the excited state. Table 3.8 list the Stokes Shift in all solvents. The Stokes Shift of all the compounds increases with increasing the polarity of the solvents. This observation agrees with the change in the molecular properties (i.e. dipole moment and geometry) of these compounds in the excited state.<sup>51</sup>



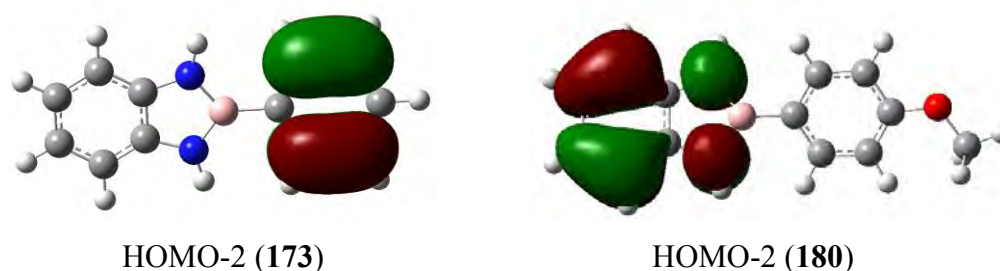
**Table 3.8** Stokes Shifts and DT-DFT [B3LYP/6-311G(\*\*)] gas phase calculated HOMO-LUMO gaps (HLGs) for **173**, **179**, **180**, **181** and **182**.

Compound	Toluene (cm <sup>-1</sup> )	THF (cm <sup>-1</sup> )	DCM (cm <sup>-1</sup> )	MeCN (cm <sup>-1</sup> )	DMSO (cm <sup>-1</sup> )	HLGs (eV)
<b>173</b>	5600	6000	6900	7800	9300	4.32
<b>179</b>	5600	6000	7200	7600	9100	4.32
<b>180</b>	5400	4800	5900	6300	7000	4.38
<b>181</b>	6700	7300	8300	8400	9100	4.15
<b>182</b>	5500	7000	7700	8200	8600	3.97

The comparison of the emission data for **173**, **189**, **180**, **181** and **182**, shows that the emission and the Stokes Shift data for compound **173** and **179** are, in general, similar. The emission maxima for these compounds are close to *ca* 300 nm in toluene, which gradually increase to *ca* 400 nm with increasing the solvent polarity to DMSO. The similarities in the photophysical behaviour of these compounds were further confirmed by computational calculations which revealed these compounds to have the same HOMO-LUMO gap of 4.32eV (Table 3.8). This clearly contrasts with the photophysical data of compounds **181**, **183** and **184**.

The emission spectra of compound **180** show emission bands which are blue shifted (hypsochromically shifted) relative to that of **173**. In addition, the Stokes Shifts of this compound are, in all solvents, lower than those of compound **173** (Table 3.8). The reasons for the deviation of the photophysical data for **180** from that of **178** are not completely clear as yet; however, these observations might perhaps be due to the *para*-donor properties of methoxy group which mesomerically donate the electron into the system causing a slight dipole inversion up on S<sub>0</sub>→S<sub>1</sub> excitation, which in turn destabilise the HOMO by increasing its energy. Such scenarios have also been reported for other three-coordinate boron compounds.<sup>70,71</sup> The destabilisation of the HOMO in compound **180**, relative to that of **173**, was confirmed computationally which revealed that, indeed the HOMO-LUMO gap of **173** (4.32 eV) is smaller than that of **180** (4.38 eV) Table 3.8. This situation was further supported by the difference observed in the HOMO-2 of the two compounds (**Figure 42**). The HOMO-2 orbitals in compound **173** are mainly localised on the phenyl part, whereas, in compound **180**,

these orbitals are located on the 1,3,2-benzodiazaborolyl part of the molecule (**Figure 42**).



**Figure 42: HOMO-2 of compounds 178 and 180**

The photophysical behaviour of **173** clearly contrasts with that of **179** and **180**. The emission maxima of these compounds are bathochromically shifted relative to those of compound **173**, which results in extremely large Stokes Shifts exhibited by these compounds (Table 3.7 and 3.8). A Similar behaviour has been reported for sulphur containing 1,3,2-benzodiazaborole compounds and was attributed to the destabilisation of the excited state,  $S_1$ , of these compounds which rapidly undergo deactivation to the triplet state,  $T_1$ , through intersystem crossing (ISC) process.<sup>48,49,72</sup> ISC have been demonstrated to be accelerated by the incorporation of heavy atom like sulphur, which have been shown to promote spin-orbit coupling in the molecule.<sup>48,49</sup>

The deactivation of the excited state,  $S_1$ , to the triplet state,  $T_1$ , stabilises the HOMO of the compound which leads to the narrowing of the HOMO-LUMO gap (HLGs). The introduction of a sulphur atom (i.e. in compounds **181** and **182**) in the 1,3,2 benzodiazaborole compounds indeed leads to the narrowing of HLGs. This effect was confirmed with DFT calculations which also revealed that the HLGs of sulphur containing compound (**181**) (4.15 eV) and **182** (3.97 eV) are narrower than the HLG for **173** (4.32 eV).

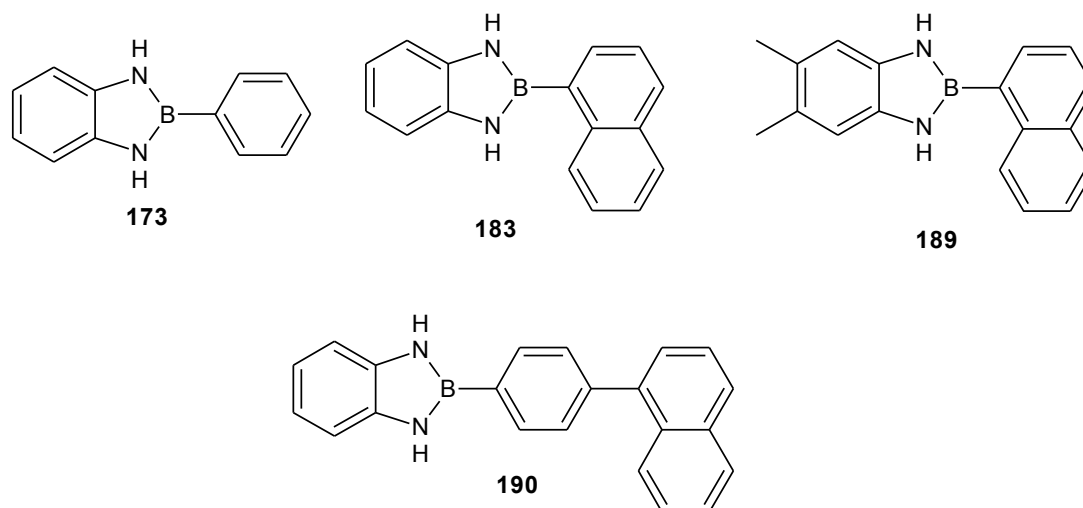
### 3.6.1.3 Conclusion

From the results obtained in this section, it can be concluded that the introduction of a methoxy group in the *meta*-position does not essentially influence the position of the emission maxima; conversely, the introduction of the methoxy group in the *para*-position leads to hypsochromic shift of the emission bands. The incorporation of the

sulphur-containing moieties at the 2 position of 1,3,2-benzodiazaborole compound has proven beneficial as it leads to the bathochromic shifts of the emission bands.

### 3.6.2 The effect of increasing $\pi$ -conjugation length

#### 3.6.2.1 UV-Vis Absorption Spectroscopy of Compounds 173, 183, 189 and 190



**Figure 57: Compounds 173, 183, 189 and 190**

The following section is aimed at investigating the influence of increasing  $\pi$ -conjugation length and the effect of introducing the phenyl spacer between the 1,3,2-benzodiazaborolyl and naphthyl groups (i.e. going from **183** to give **190**), on the photophysical properties of these compounds. In order to achieve our goals, the UV-visible spectroscopic studies of compounds depicted on figure 57 were carried out. In addition, these studies were complemented with DFT calculations which are aimed at examining the influence of changing the conjugation lengths, on the HOMO-LUMO energy gaps of these compounds. The UV/vis absorption maxima for compound **173**, **183**, **189** and **190** are summarised in Table 3.9 below.

**Table 3.9:** Experimental absorption data for compounds **173**, **183**, **189** and **190** collected at 22° C in the concentration ranging from  $1.0 \times 10^{-6}$  to  $1.0 \times 10^{-5}$  M.

Compound	Toluene (nm)	THF (nm)	DCM (nm)	MeCN (nm)	DMSO (nm)
<b>173</b>	300	301	300	297	303
<b>183</b>	304	307	301	304	313
<b>189</b>	311	319	311	315	324
<b>190</b>	307	308	308	306	310

From the table above, it can be seen that the Uv-visible absorption spectra of the compounds under investigation are dominated by intense absorption bands in a narrow range 300-324 nm going from toluene to DMSO, respectively. In general the position of these bands are slightly red shifted with increasing the polarity of the solvent (maximum  $\Delta\lambda = 13$  nm). The small shifts in the absorption maxima are suggestive of a lack of solvatochromism, which points to the small dipole moments of these compounds in the ground state. The low dipole moments were confirmed with DFT calculation, and ranges from 0.1379 to 0.8433 D (Table 3.10).

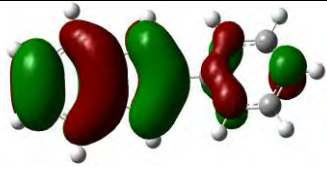
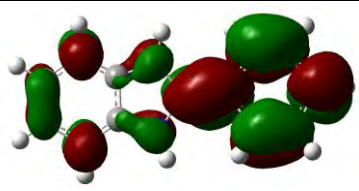
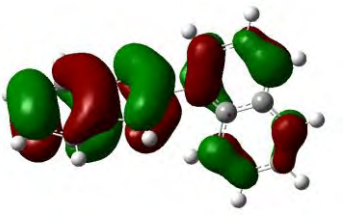
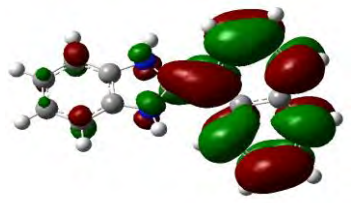
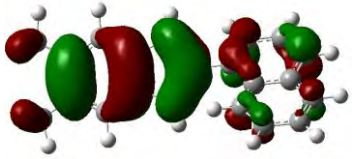
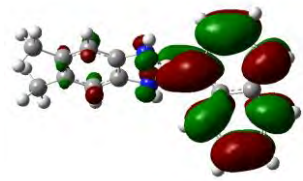
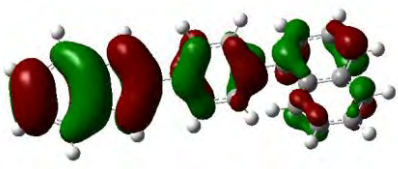
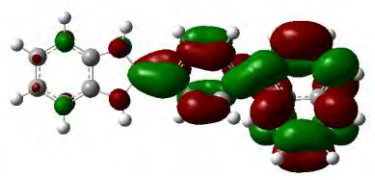
According to theoretical calculations, the absorption bands of these compounds are assigned to the transitions from the HOMO into the LUMO of the molecule. The calculated absorption maxima are in good agreement with the experimental data with the maximum difference of only 15 nm<sup>†</sup>. The HOMO of compounds under investigation are all located on the 1,3,2-benzodiazaborolyl part of the molecule with small contribution of  $\pi$ -orbitals of the attached  $\pi$ -system. The LUMO are mainly represented by the attached  $\pi$ -system.

<sup>†</sup> Note, the difference between the calculated absorption maxima and the experiment maxima is due to the fact that the calculated values are done in a gas phase which only assumes a single geometry, whereas the experimental values include all possible geometries present in solution.

**Table 3.10:** DT-DFT [B3LYP/6-311G(\*\*)] calculated absorption data for compounds **173**, **183**, **189**, and **190**.

Compound	$\lambda_{\text{obs}}(\text{nm})^{\text{a}}$	$\lambda_{\text{calc}}(\text{nm})$	$\Delta\lambda^{\text{b}}$	$\mu_{\text{g}}(\text{D})$	Orbital
<b>173</b>	297	287	-10	1.0833	HOMO→LUMO
<b>183</b>	313	324	11	0.7700	HOMO→LUMO
<b>189</b>	324	341	17	0.1379	HOMO→LUMO
<b>190</b>	308	323	15	0.8433	HOMO→LUMO
<sup>a</sup> Data collected in MeCN. <sup>b</sup> $\lambda_{\text{obs}} - \lambda_{\text{calc}}$ .					

**Table 3.11:** DT-DFT [B3LYP/6-311G(\*\*)] gas phase calculated HOMO-LUMO frontier orbitals for compounds **13**, **183**, **189**, and **190**.

Compounds	HOMO	LUMO
<b>173</b>		
<b>183</b>		
<b>189</b>		
<b>190</b>		

Based on the similarities in the photophysical behaviour of all the compounds in this section, it can be safely deduced that the extension of  $\pi$ -conjugation length from

phenyl group (compound **173**) to naphthyl group (compound **183**) and the insertion of phenyl spacer between 1,3,2-benzodiazaborolyl and naphthyl moieties (compound **188**) does not have any significant influence on the photophysical properties of these compounds in the ground state.

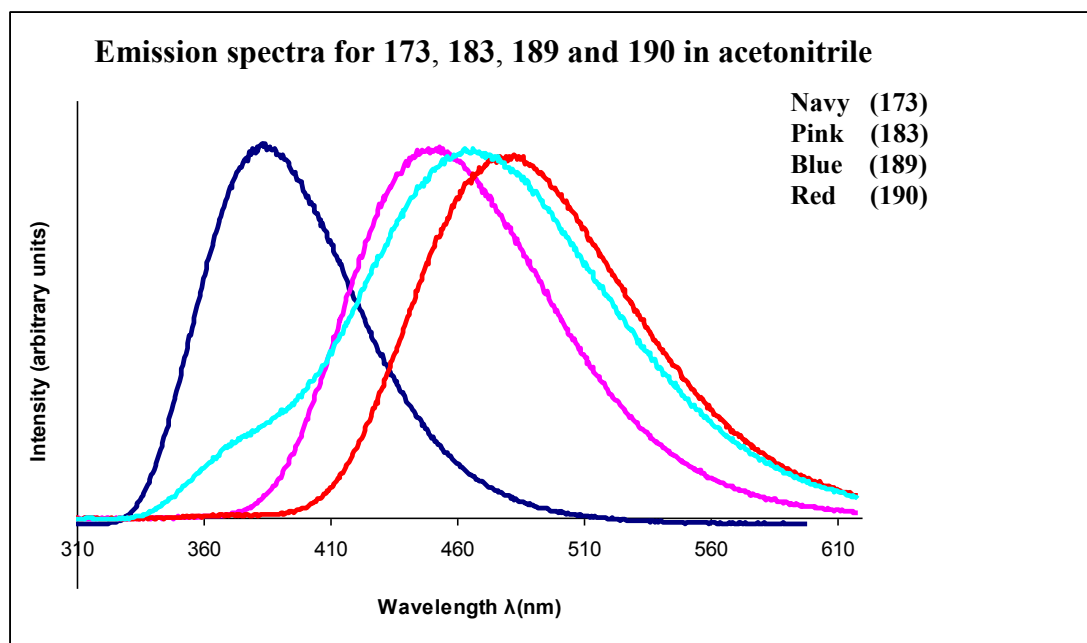
### 3.6.2.2 Emission Spectroscopy of Compounds 173, 183, 189 and 190

The emission spectra of these compounds were acquired in a range of deferent solvents. The DCM solutions of these compounds reveal blue emission when irradiated with a hand held UV-lamp. Their emission spectra are dominated with emission bands in a broad range of 360 nm (**173**) to 491 nm (**189**). The position of these bands are markedly influenced by the polarity of the solvent used, pointing to the presence of significant solvatochromism.

The spectral properties of compound **173** were compared to the spectral properties of the other compounds. From table 3.12 below, it can be seen that the emission bands for compounds **183**, **189** and **190** are bathochromically shifted relative to the emission bands of **173** in all solvents. This effect has also been noted by several authors,<sup>47, 48</sup> and was attributed to the extension of  $\pi$ -conjugation interactions (i.e. better  $\pi$ -communication) between 1,3,2-benzodiazqaborolyl and the attached  $\pi$ -rings. This phenomenon is best illustrated by the emission spectra in Figure 58 below.

**Table 3.12** Emission data for compounds **173**, **183**, **189**, and **190** collected at 22° C in the concentrations ranging from  $1.0 \times 10^{-6}$  to  $1.0 \times 10^{-5}$  M.

Compound	Toluene (nm)	THF (nm)	DCM (nm)	MeCN (nm)	DMSO (nm)
<b>173</b>	360	368	379	387	422
<b>183</b>	397	430	440	453	465
<b>189</b>	433	451	465	481	491
<b>190</b>	397	434	433	450	470



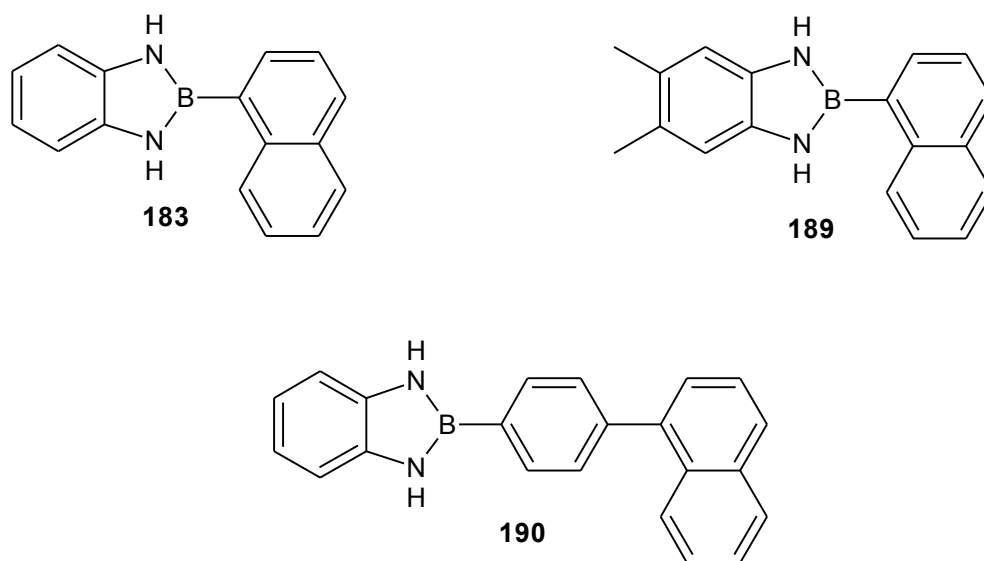
**Figure 44: Emission spectra for compounds 173, 183, 189 and 190 in MeCN.**

The bathochromic shift of the emission maxima and the increase in the Stokes shifts (Table 3.13) observed for compounds **183**, **189** and **190** relative to that of compound **173** clearly indicates that the elongation of  $\pi$ -conjugation length on the boron atom are largely beneficial for the improvement of the photophysical properties of these compounds.

**Table 3.13:** Stokes Shifts and DT-DFT [B3LYP/6-311G(\*\*)] gas phase calculated HOMO-LUMO gaps (HLGs) for **173**, **183**, **189** and **190**.

Compound	Toluene (cm <sup>-1</sup> )	THF (cm <sup>-1</sup> )	DCM (cm <sup>-1</sup> )	MeCN (cm <sup>-1</sup> )	DMSO (cm <sup>-1</sup> )	HLGs (eV)
<b>173</b>	5600	6000	6900	7800	9300	4.32
<b>183</b>	7300	9300	10500	10800	10400	3.83
<b>189</b>	9100	9200	10700	11000	10500	3.64
<b>190</b>	7400	9400	9400	10500	10200	4.21

Now that we have determined the influence of extending the  $\pi$ -conjugation length on the emission spectra, attention was then turned to exploring the influence of introducing phenyl spacer between 1,3,2-benzodiazaborolyl and naphthyl groups ( i.e. going from compound **3183** to **190**) and the effects of the methyl groups ( i.e. going from compound **183** to compound **189**), on the photophysical characteristics of these compounds (**Figure 45**).

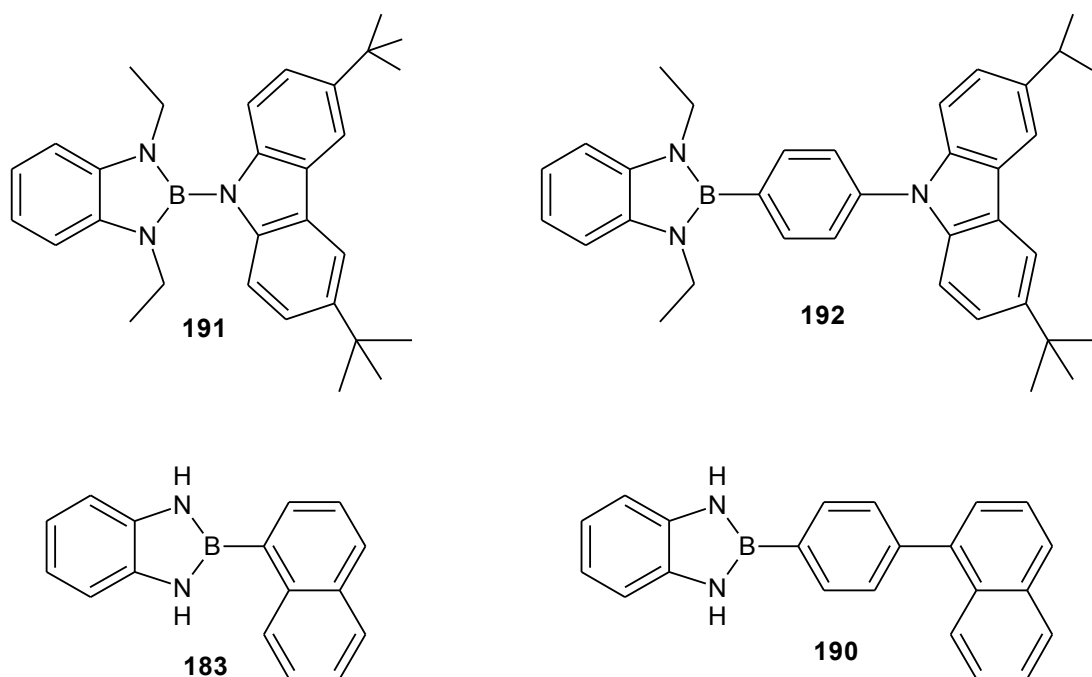


**Figure 45: Compounds 183, 183 and 190.**

In order to conduct these investigations, the spectroscopic data for compound **183** will be compared to the spectroscopic data for compounds **189** and **190**. The emission maxima for compound **190** are quite similar to the emission maxima for compound **183** with the maximum difference of only  $\lambda = 5$  nm in DMSO. In general, the similar trend is also observed in the Stokes Shifts of these compounds.

Our results contrast with the findings of Chrostowska *et al.*<sup>52</sup> who reported that the insertion of the phenyl spacer between the carbazolyl group and 1,3,2-benzodiazaborolyl group (i.e. in going from compound **191** to compound **192**, **Figure 46**) led to the enhancement of the Stokes Shifts and the bathochromic shifts of the emission maxima for compound **192** relative to that of compound **191** (**Figure 46**).<sup>52</sup>





**Figure 46: Compounds 183, 190, 191 and 192**

According to our theoretical calculations, the formal insertion of the phenyl spacer between the naphthyl and the 1,3,2-benzodiazaborolyl group lead to destabilisation of the LUMO from  $-7.082$  eV (**183**) to  $-7.555$  eV (**190**) by  $0.472$  eV. This effect raises the LUMO of compound **188** leading to the widening of the HOMO-LUMO gap. The latter effect was also confirmed with computational calculations which showed that the HOMO-LUMO gap (HLG) of compound **190** ( $4.21$  eV) is indeed larger than the HLG of compound **185** ( $3.83$  eV), Table 3.13.

In contrast to the spectroscopic data for compound **190**, the emission maxima of methylated compound (**189**) are all bathochromically shifted relative to those of compound **185** in all solvents. Similarly, the Stokes Shifts of compound **189** are, in general, larger than the Stokes shifts of compound **185**. These observations clearly indicate that the introduction of the methyl groups has a significant influence on the electronic processes of these compounds. Soloway and Kawanashi have reported that the introduction of electron-donating groups, at the backbone of the 1,3,2-benzodiazaborole compounds, shifts the emission maxima to a longer wavelength. In a related study, Ma and Sapochak also confirmed that introduction of the electron donating methyl groups on the backbone of a luminescent compound leads to the bathochromic shift of the emission maxima.<sup>17,60,73,74</sup>

Based on the above interpretations, the bathochromic shifts of the emission maxima observed for compound **189** (relative to those of compound **185**) is attributed to the presence of the methyl groups which inductively pushes the electron density into the 1,3,2-benzodiazaborolyl ring. This effect enhances the availability of the lone pair of electrons on the nitrogen atoms for better interaction with the vacant  $2p_z$ -orbital on the boron atom. This phenomenon improves  $\pi$ -communication between the 1,3,2-benzodiazaborolyl ring and the naphthyl ring which consequently stabilised the HOMO of the compound. The stabilisation of the HOMO lowers the HOMO, thereby shifting the emission maxima to the longer wavelengths. To confirm whether the introduction of the methyl groups indeed leads to the narrowing of HLG, DFT calculations for compound **185** and compound **189** were conducted and the results compared. The values show that the HLG of compound **189** (3.64 eV) is certainly narrower than the HLG for **185** (3.83 eV).<sup>17,60, 73, 74</sup>

### 3.6.2.3 Conclusion

From this study, it can be concluded that the elongation of  $\pi$ -conjugation length on the 2 position of the 1,3,2-benzodiazaborolane compounds leads to better orbital overlap between HOMO (mainly represented by 1,3,2-boenzodiazaborolyl group) and LUMO (mainly located on the attached  $\pi$ -ring). This effect has been demonstrated to narrow the HLG of these molecules thus shifting the emission maxima to longer wavelength. The formal insertion of a phenyl spacer between 1,3,2-boenzodiazaborolyl group and naphthyl ring have proven to have no significant effect on the photophysical properties of these compounds. The introduction of the methyl groups on the backbone of 1,3,2-boenzodiazaborole compounds also proved to be beneficial for the photophysical properties of these compounds resulting in bathochromic shifts of the emission maxima.

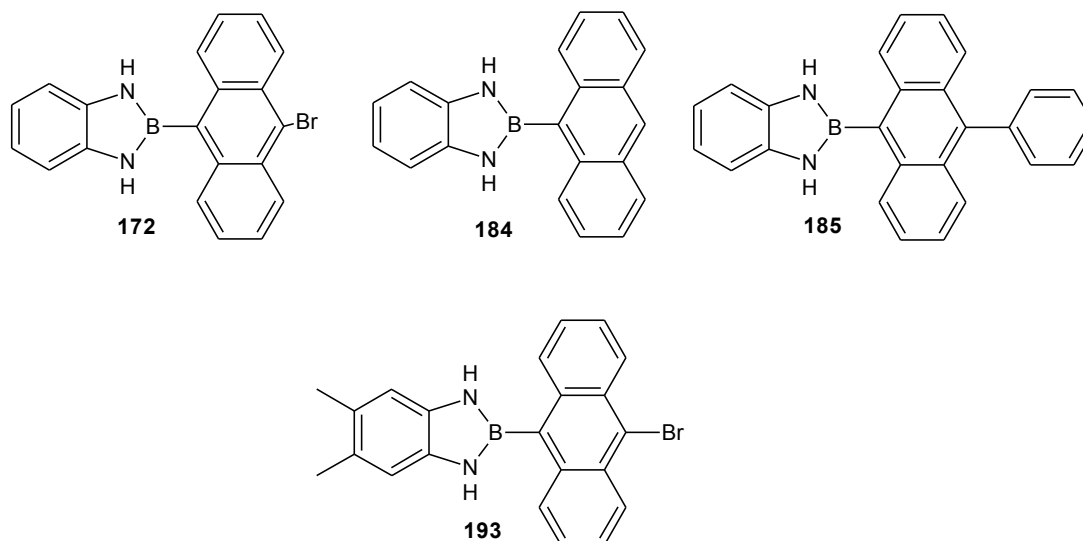
### 3.6.3 The influence of 1,3,2-benzodiazaborolyl unit on the photochemical properties of anthracene.

Anthracene and its derivatives have been studied extensively in the past decade because of their fascinating spectroscopic and photophysical properties.<sup>75</sup> Anthracene is a blue emissive fluorophore with an absorption maximum of  $\lambda = 377$  nm, and has found application as a photoluminescent compound in many diodes and batteries.<sup>64</sup> Regardless of the vast majority of spectroscopic and photophysical studies on anthracene and its derivatives conducted in the past, there are only few reports in the literature which describe the synthetic and luminescent studies of organoborane compounds containing anthryl units.<sup>23,66,76</sup> Particularly, anthryl-functionilised 1,3,2-benzidoazaborole compounds have, to the best of our knowledge, never been synthesised and their photophysical properties reported.

1,3,2-Benzodiazaborolyl group has been demonstrated in section 3.6.1 and 3.6.2 to play a crucial role in the luminescent characteristics of 2-arylbenzo-1,3,2-diazaborole compounds, whilst anthracene derivatives are well known for their intriguing optical properties. With these ideas in mind, we designed and synthesised compounds with anthryl units and 1,3,2-benzodiazaborolyl groups within one molecule in order to investigate the role and the influence of 1,3,2-benzodiazaborolyl groups on the photophysical and the electronic characteristics of the synthesised anthryl-functionalised benzo-1,3,2-diazaborole compounds. In addition, DFT studies were conducted to explore the influence of substituents on the HOMO-LUMO energy gap and the LUMO energies.

To pursue our objectives, the absorption and emission characteristics of compounds **190**, **191** and **194** will be compared to the photophysical properties of **193** which, in this study, will be treated as a standard molecule (**Figure 47**).

### 3.6.3.1 UV-Vis Absorption Spectroscopy of Compounds 172, 184, 185 and 193



**Figure 47: Compounds 172, 184 and 185, 193**

The UV/visible absorption spectra for compounds **172**, **184**, **185** and **193** were acquired in different solvents and their absorption maxima are summarised in Table 3.14. Generally, all compounds under investigation display intense absorption bands in a very close range of 385-403 nm whose absorption maxima are insensitive towards the change in the polarity of the solvent used. The absence of solvatochromism is consistent with little or no change in charge distribution upon excitation, which points to the presence of low dipole moments in the ground state.

**Table 3.14:** Experimental absorption maxima for compounds **172**, **184**, **185** and **193** collected at 22° C in the concentration ranging from  $1.0 \times 10^{-6}$  to  $1.0 \times 10^{-5}$  M.

Compound	Toluene (nm)	THF (nm)	DCM (nm)	MeCN (nm)	DMSO (nm)
<b>172</b>	401	400	400	383	403
<b>184</b>	401	400	400	398	402
<b>185</b>	386	385	386	387	390
<b>193</b>	395	395	397	393	398

**Table 3.15:** DT-DFT [B3LYP/6-311G(\*\*)] calculated absorption data for compounds **172**, **184**, **185** and **193**

Compound	$\lambda_{\text{obs}}(\text{nm})^{\text{a}}$	$\lambda_{\text{calc}}(\text{nm})$	$\Delta\lambda^{\text{b}}$	$\mu_g (\text{D})$	Orbital
<b>172</b>	383	462	21	0.8851	HOMO→LUMO
<b>184</b>	398	485	87	1.6612	HOMO→LUMO
<b>185</b>	387	444	37	1.3970	HOMO→LUMO
<b>193</b>	393	393	0	0.8315	HOMO→LUMO
<sup>a</sup> Data collected in MeCN. <sup>b</sup> $\lambda_{\text{obs}} - \lambda_{\text{calc}}$					

The low dipole moments in the ground state were confirmed with DFT calculations which showed a close range of 0.8315-1.6612 D. The calculated absorption maxima for compounds **172**, **184** and **185** are bathochromically shifted by 21 nm, 37 nm and 87 nm in comparison to the experimental values, respectively. These observations have also been noted by other authors and are attributed to the differences in the geometries found by computational and experimental means. However, it is quite interesting to note that the calculated and experimental absorption maxima for **185** are similar. Logically, this effect is presumably due to the similarity in the rotameric conformers of this compound in gas phase and in the solution.<sup>48, 52, 67</sup>

According to theoretical calculations, the observed intense absorption bands reflect the transition from HOMO to LUMO. The HOMO for all the derivatives are mainly represented by  $\pi^*$ -orbital of the anthracenyl unit with small contribution of  $\pi^*$ -orbital of the benzodiazaborolyl group except for compound **185**. The HOMO of this compound is evenly distributed throughout the entire compound. The LUMO of all compounds under investigation are mainly localised on the anthryl unit with  $2p_z$ -orbital contribution of the boron atom.

The distribution of HOMO and LUMO on these compounds clearly indicates that the vacant  $2p_z$ -orbital on the boron atom do not form part of the HOMO as literature precedent has suggested.<sup>52</sup>

### 3.6.3.2 Emission Spectroscopy of Compounds 172, 184, 185 and 193

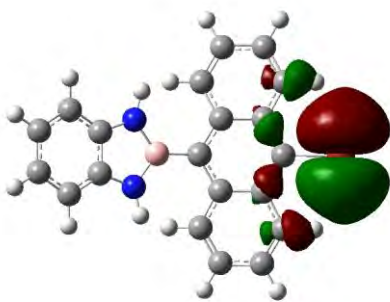
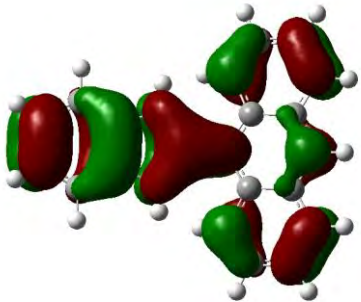
The acetonitrile solutions of all species under investigation exhibited yellow-green luminescence under UV irradiation. The emission spectra of these compounds are dominated by strong emission bands whose position depends on the polarity of the solvent used. From table 3.16, it is evident that the emission maxima of all compounds are bathochromically shifted with increasing the polarity of the solvent, thus indicating the presence of positive solvatochromism. For example, the emission band for compound **185** (535 nm, in toluene) is red shifted to 548 nm, 558 nm, 584 nm and 590 in THF, DCM, MeCN and DMSO, respectively.<sup>48, 51, 52, 58</sup>

**Table 3.16** Emission data for compounds **172**, **184**, **185** and **193** collected at 22° C in the concentrations ranging from  $1.0 \times 10^{-6}$  to  $1.0 \times 10^{-5}$  M.

Compound	Toluene (nm)	THF (nm)	DCM (nm)	MeCN (nm)	DMSO (nm)
<b>172</b>	481	509	523	544	579
<b>184</b>	535	548	558	584	590
<b>185</b>	475	485	504	522	557
<b>193</b>	480	481	504	523	536

Similarly, the Stokes Shifts of these compounds follow the same trends as the emission maxima with the larger Stokes Shift in a more polar solvent (Table 3.17). Interestingly, the emission maxima for compound **184** are slightly red shifted in all solvents when compared to those of the brominated derivative **172** with the maximum difference of  $\Delta\lambda_{\text{max}} = 22$  nm in DMSO. This effect has been noted and was attributed to the presence of bromine atom which significantly changes the nature of frontier orbital, due to its stronger electron-withdrawing abilities when compared to the carbon directly bonded to it. As a consequence, the LUMO of the molecule is stabilised, leading to narrowing of the HOMO-LUMO gaps. The change in the nature of frontier orbitals on the introduction of bromine atom was confirmed computationally (Table 3.17).<sup>48,77</sup>

**Table 3.17:** Comparison of DT-DFT [B3LYP/6-311G(\*\*)] HOMO-1 calculated for compounds **172** and **184**

	Compound <b>172</b>	Compound <b>184</b>
HOMO-1		

From the table above, it is evident that bromine plays an essential role in the nature of frontier orbitals. In compound **184**, the HOMO-1 is represented by  $\pi$ -orbitals which are distributed throughout the whole molecule with significant contribution of the non-bonding orbitals on the nitrogen atom and the vacant  $2p_z$ -orbital on the boron atom. Conversely, the HOMO-1 of compound **172** is localised on the bromine atom. In line with theoretical calculation, the bromination, certainly lead to the stabilisation of the LUMO from  $-2.04$  eV (**172**) to  $-2.26$  eV (**184**) (Table 3.18). This effect is accompanied by the narrowing of HOMO-LUMO gap from  $2.79$  eV (**184**) to  $2.68$  eV (**3.33**) as anticipated.<sup>48, 77</sup>

**Table 3.18** Stokes Shifts for compounds **172**, **184**, **185** and **193**.

Compound	Toluene (cm <sup>-1</sup> )	THF (cm <sup>-1</sup> )	DCM (cm <sup>-1</sup> )	MeCN (cm <sup>-1</sup> )	DMSO (cm <sup>-1</sup> )
<b>172</b>	4100	5400	5900	6700	7000
<b>184</b>	6200	6800	7100	8000	8300
<b>185</b>	4900	5400	6100	6900	7600
<b>193</b>	4500	4500	5300	6300	6500

In contrast to the emission maxima, the Stokes Shifts of compounds **184** are generally larger than those for compound **172**. The Stokes Shifts are expected to follow the same trends as the emission maxima; however, it is clearly not the case with

compound **184** and **185**. The reason as to why this observation is witnessed is not as yet known.

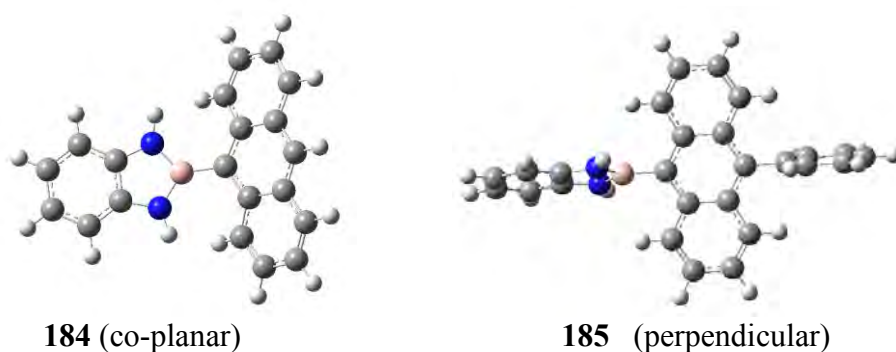
**Table 3.19** : Selected photophysical data DT-DFT [B3LYP/6-311G(\*\*)] gas phas calculated for compounds **172**, **184**, **185** and **193**.

Compounds	$\lambda_{\text{abs, max}}^{\text{a}}$ (nm)	$\lambda_{\text{emm, max}}^{\text{a}}$ (nm)	S.S. <sup>b</sup> (cm <sup>-1</sup> )	HOMO (eV)	LUMO (eV)	HLGs (eV)
<b>172</b>	383	544	7700	-4.9411	-2.2600	2.6815
<b>184</b>	398	584	8000	-4.7462	-2.1837	2.5625
<b>185</b>	387	522	6700	-4.8346	-2.0441	2.7905
<b>193</b>	393	523	6300	-4.9303	-1.7790	3.1514
<sup>a</sup> Data collected in MeCN. <sup>b</sup> Stokes Shifts (data collected in MeCN)						

The comparison of the emission maxima for compound **184** and compound **185** shows that the emission bands for **185** are hypsochromically shifted when compared to those of compound **184**. These data is in good agreement with the Stokes shifts. From the table, it can be seen that the Stokes shifts of compounds **185** are indeed lower than the values obtained for **184**. The bathochromic shift on the emission maxima and larger Stokes shifts witnessed for **184** relative to those of compound **185** are rationalised in terms of planarity.

According to geometry optimisation, the anthryl unit in compound **184** is almost co-planar to the 1,3,2-diazaborolyl group, however, in compound **185** this group is oriented in the perpendicular position relative to 1,3,2-diazaborolyl group (**figure 48**). According to Weber *et al.*<sup>48</sup> the orientation of the  $\pi$ -system directly attached to boron plays an essential role in the photophysical properties of three coordinate boron compounds because maximum orbital overlap between the vacant 2p<sub>z</sub>-orbital on boron and  $\pi$ -orbital on the carbon directly attached to boron would occur if the two functionalities are co-planer to each other.<sup>48</sup>





**Figure 48: Orientations of compounds 184 and 185**

Based on this observation, the hypsochromic shift and the smaller Stokes shifts exhibited by compound **185** relative to those of **184** may be attributed to the lack of maximum  $\pi$ -orbital overlap between the  $2p_z$ -orbital on boron and  $\pi$ -orbital on the carbon directly attached to boron for compound **185** relative to compound **184**. This effect leads to the destabilisation of HOMO from  $-4.9303\text{eV}$  (**185**) to  $-4.8346\text{ eV}$  (**193**) which consequently broaden the HOMO-LUMO energy gap from  $2.7905$  (**184**) to  $3.1514\text{ eV}$  (**185**).

### 3.6.3.3 Conclusion

From the results obtained in this section, it can be concluded that the introduction of the bromine on 10 position of the anthryl ring leads to bathochromic shift of the emission maxima. The LUMO of compounds investigated are mainly located on the anthryl unit with a small contribution of the vacant  $2p_z$ -orbital on the boron atom. These findings are in agreement with recent reports by Weber and co-workers.<sup>71</sup>

### **3.7 Overall conclusion**

One of the objectives of this project were focused on the synthesis of a range of 2-arylbenzo1,3,2-diazaborole compounds from the corresponding aryl boronic acids and 1,2-diaminobenzene. From table 3.4 (section 3.4) it can be seen that 2-arylbenzo1,3,2-diazaborole compounds were successfully synthesised in excellent yields ranging from 43% to 93%.

This project was also aimed at investigating the spectroscopic characteristics of these compounds by acquiring and studying their absorption and emission spectra. The data obtained revealed the lack of significant solvatochromism for all the compounds which is indicative of the presence of low dipole moments of these compounds in the ground state. These values were confirmed computationally which showed low calculated dipole in a range of 0.1379 to 2.2773 D. In the excited state, all the chromophores are influenced by the polarity of the solvent used pointing to the presence of positive solvatochromism. The introduction of a donor group such as methylthio (MeS) and the introduction of bromine atom on the anthracenyl moiety have proven beneficial for the emission maxima of the species under investigation.

The extension of  $\pi$ -conjugation length at the 2 position of these species and the methylation at the back bone of the 1.3.2-benzodiazaborolyl group leads to bathochromic shifts of the emission maxima, which in turn lead to large Stokes shifts of up to 11000  $\text{cm}^{-1}$ . Alternatively, the formal insertion of the phenyl spacer between the naphthyl ring and the 1.3.2-benzodiazaborolyl group does not have any influence on the photophysical properties of these compounds.

The HOMOs of all the chromophore are purely represented by the 1.3.2-benzodiazaborolyl group except for anthracenyl-functionalised benzo-1,3,2-diazaborolane compounds in which the HOMO are located on the  $\pi$ -system with no contribution of the vacant  $2p_z$ -orbital of the boron atom. The large Stokes shifts and significant solvatochromism displayed by these compounds are suggestive of potential application in organic light emitting diodes (OLED) as emitters.

## 3.8 References

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1. Coyle, J. D., *Introduction to Organic Photochemistry*. First ed.; New York, 1986.
2. Coxon, J. M., Halton, B., *Organic Photochemistry*. Second ed.; Cambridge University Press: New York and London, 1987.
3. Coxon, J. M., Halton, B., *Organic Photochemistry*. First ed.; Cambridge University Press: New York and London, 1974.
4. Lakowicz, J. R., *Principals of Fluorescence Spectroscopy*. Third ed.; Kluwer Academic Plenum Publishers, New York, 2006.
5. Rendell, D., *Fluorescence and Phosphorescence*. John Wiley and Sons: 1987.
6. Sibley, S., Tompson, M. E., Borrows, P. E., Forrest, S. R., *In Optoelectronic Properties of Inorganic Compounds*, Roundhill, D. M., Fackler, J. P., Jr., Eds., Plenum Press, New York, 1999; p 29-54.
7. Colvin, V. L., Schlamp, M. C., Allvisatos, A. P., *Nature* **1994**, 370 354 and references therein.
8. Drexhage, K. H., in *Topics in Applied Physics: Dye Lasers*. Springer, New York, 1977; Vol. 1, p 144.
9. Gold, H., *The Chemistry of Synthetic Dyes*. Academia, New York, 1971; Vol. 5, p 535.
10. Helfrich, W., Schneidere, W. G., *Phys. Rev. Lett.* **1965**, 14, 229.
11. Tang, W. C., VanSlyke, S. A., *Appl. Phys. Lett.* **1987**, 15, 913 and references therein.
12. Curioni, A., Boero, M., Wanda, A., *Chem. Phys. Lett.* **1998**, 294, 263.
13. Burrows, P. E., Shen, Z., Bulovic, V., McCarty, D. M., Forrest, S. R., *J. Appl. Phys.* **1996**, 79, 7991.
14. Halls, M. D., Schlegel, H. B., *Chem. Mater.* **2001**, 13, 2632.
15. Jang, H., Do, M-L., Kim, Y., Kim, G. J., Zyung, T., Do, Y., *Synthetic Metals* **2001**, 121, 1669.
16. Shi, Y.-W., Shi, M-M., HuangJ-C., Chen, Z-H., Wang, M., Liu, X-D., Ma, G-Y., Xu, H., Yang, B., *Chem. Commun* **2006**, 1941.
17. Sapochak, S. L., Padmaperuma, A., Washton, N., Endrino, F., Schmett, T.G., Marshall, J., Fogarty, D., Burrows, P. E., Forrest, R. S., *J. Am. Chem. Soc.* **2001**, 123, 6300.
18. Chen, C. H., Shi, J., *Coord. Chem. Rev.* **1998**, 171, 161.
19. Kido, J., Lizumi, Y., *Appl. Phys. Lett* **1998**, 73, 2721.
20. Murata, H., Merritt, C. D., Mattoussi, H., Kafafi, Z. H., *Int. Soc. Opt. Eng.* **1998**, 3476, 88.
21. Sano, T., Nisho, Y., Hamada, Y., Takahashi, H., Usuki, T., Shibata, K., *J. Mater. Chem* **1999**, 10, 157.
22. Hopkins, A. T., Meerholz, K., Shaheen, S., Anderson, M. L., Schimidt, A., Kippelen, B., Padias, A. B., Hall, H. K., Peyghambarian, N., Armstrong, N. R., *Chem. Mater.* **1995**, 8, 344.
23. Entwistle, D. C., Mader, T. B., *Chem. Mater.* **2004**, 16, 4574.
24. Williams, J. L. R., Glogowski, M. E., *J. Organomet. Chem.* **1981**, 218, 137.
25. Doty, J. C., Williams, J. L. R., Grisdale, P. J., *J. Org. Chem* **1971**, 36, 544.
26. Doty, J. C., Williams, J. L. R., Grisdale, P. J. Babb, B., Glogowski, M., *J. Organomet. Chem.* **1972**, 38, 229.
27. Jia, L.-W., Song, D., Wang, S., *J. Org. Chem* **2002**, 68, 701.
28. Liu, F.-S., Wu, Q., Schmider, H. L., Aziz, H., Hu, N.-X., Popovic, Z. Wang, S., *J. Am. Chem. Soc.* **2000**, 122, 3671.
29. Noda, T., Shirota, Y., *J. Am. Chem. Soc.* **1998**, 120, 9714.
30. Shirota, Y., *J. Mater. Chem* **2004**, 15, 75.

31. Branger, C., Lequan, M., Lequan, R. M., Barzoukas, M., Fort, A., *J. Mater. Chem* **1996**, 6, 555.
32. Doi, H., Kinoshita, M., Okumoto, K., Shiota, Y., *Chem. Mater.* **2003**, 15, 1080.
33. Wang, S., Zhao, Q.-Y., Lu, Z.-H., Li., Jia, W.-L. Yuan, Y. Y., Moran, M. J., *J. Mater. Chem* **2005**, 15, 3326.
34. Jia, L.-W., Wang, S., Feng, X. D., Bai, D. R., Lu, Z.-H., Vamivounis, G., *Chem. Mater.* **2005**, 17, 164.
35. Tse, S. C., So, S. K., *Appl. Phys. Lett* **2006**, 89, 262102.
36. Jia, L.-W., Wang, S., Bai, R.-D., McCormick, T., Liu, Q.-D., Motala, M., Wang, R.-Y., Seward, C., Tao, Y., *Chem. Eur. J* **2004**, 10, 994.
37. Xiao, L., Chen, Z., Qu, B., Luo, J., Kong, S., Gong, Q., Kido, J., *Adv. Mater* **2011**, 23, 926.
38. Lowry, S. B., S., *Chem.-Eur. J.* **2006**, 12, 7970.
39. Chou, P.-T., Chi, Y., *Chem.-Eur. J.* **2007**, 13, 380.
40. Yang, H. X., Neher, D., Hertel, D., Daubler, T. K., *Adv. Mater.* **2004**, 16, 16.
41. Chujo, Y., Matsumi, N., *Organometallics* **2001**, 20, 2425.
42. Kitamura, N., Funahashi, A., Sakuda, E., *Inorg. Chem* **2006**, 45, 10670.
43. Marder, T. B., Ma, D. G., Wang, L. X., Beeby, A., Zhao, G.J., Wong, W. Y., Ho, L. C., *Adv. Funct. Mater* **2008**, 18, 499.
44. Hudson, M. Z., Wang, S., *Dalton Trans.* **2011**, 40, 7805.
45. Hudson, M. Z., Wang, S., Helander, G. M., Lu, Z.-H., *Chem. Commun.* **2011**, 47, 755.
46. Maruyama, S., Kawanishi, Y., *J. Mater. Chem* **2002**, 12, 2245.
47. Domke, I., Stammler, H.-G., Werner, V., Neumann, B., Weber, L., *Dalton Trans.* **2006**, 3777.
48. Weber, L., Werner, V., Fox, A. M., Marder, B. T., Schwedler, S. Brockhinke, A., Stammler, Neumann, B., *Dalton Trans.* **2009**, 1339.
49. Siddle, J. S., Ward, M. R., Collings, J. C., Rutter, S. R., Porres, L., Applegarth, L., Beeby, A., Batsanov, A. S., Thompson, A., L., Howard, J. A. K., Boucekine, A., Costuas, K., Halet, F. J., Mader, T.B., *New J. Chem* **2007**, 31, 841.
50. Lothar, W., Halama, J., Werner, V., Hanke, K., Bohling, L., Chrostawska, A., Dargelos, A., Macejczyk, M., Raza, A.-L., Stammler, H.-G., Neumann, B., *Eur. J. Inorg. Chem* **2010**, 5416-5425.
51. Weber, L., Halama, J., Werner, V., Hanke, K., Bohling, L., Chrostawska, A., Dargelos, A., Macejczyk, M., Raza, A.-L., Stammler, H.-G., Neumann, B., *Eur. J. Inorg. Chem* **2010**, 5416.
52. Chrostowska, A., Halama, J., Bohling, L., Dargelos, A., Stammler, G.-H., Weber, L., Neumann, B., *Eur. J. Inorg. Chem* **2011**, 3091.
53. Johnson, J. R., Bean, F. R., *J. Am. Chem. Soc.* **1931**, 53, 711.
54. Diorazio, L. J., Widdowson, D. A., Clough, J. M., *Tetrahedron* **1992**, 48, 8073.
55. Lu, G., Frannzen, R., Zhang, Q., Xu, Y., *Tetrahedron Lett.* **2005**, 46, 4255.
56. Noth, H., Wrackmeyer, B., *Nuclear Magnetic Resonance of Boron Compounds*, . Springer-Verlag, Berlin Heidelberg, New York, 1978.
57. Wang, L., Lu, W., *Org. Lett.* **2009**, 11, 1079.
58. Weber, L., *Coord. Chem. Rev.* **2008**, 252, 1.
59. Soloway, A. H., Nyilas, E., *J. Am. Chem. Soc.* **1958**, 81, 2681.
60. Soloway, A. H., *J. Am. Chem. Soc.* **1959**, 82, 2442.
61. Yamashita, M., Nzaki, K., *Pure Appl. Chem.* **2008**, 80, 1187.
62. Yamaguchi, Y. T., T., Kobayashi, S., Wakayima, T., Matsubara, Y., Yoshida, Z., *J. Am. Chem. Soc.* **2005**, 127, 9332.
63. Zhao, G.-J., Lui, Y.-H., Han, K.-L., Dou, Y., *Chem. Phys. Lett.* **2009**, 453, 29.
64. Chan, S. C., Jang, J. P., Cherng, Y. J., *Tetrahedron* **2009**, 65, 1977.
65. Zhang, L., Urian, R. C., Liu, Y., Jen, A. K. Y., Pu, L., *Chem. Mater.* **2000**, 12, 13.
66. Wakamiya, A., Ide, T., Yamaguchi, S., *J. Am. Chem. Soc.* **2005**, 127, 14859
67. Lakowicz, J. R., *Principles of Fluorescence Spectroscopy*. Third ed.; Kluwer Academic Plenum Publisher, New York, 2006.

68. Marini, A., Munoz-Losa, A., Biancardi, A., Menncci, B., *J. Phy. Chem.* **2010**, 114, 17128, and referenes therein.
69. Mohammed, O. F., Kwon, O. -H., Othon, C.M., Zewail, A.H., *Angew. Chem. Int. Ed.* **2009**, 48, 6251
70. Meshulam, G., Berkovic, G., Kotler, Z., Ben-Asuly, A., Mazor, R., Shapiro, L., Khodorkosky, V., *Syth. Met.* **2000**, 15, 249
71. Kapturkiewicz, A., Herbich, J., Kapiuk, J., Nowacki, J., *J. Phy. Chem.* **1997**, 101, 2332.
72. Weber, L., Eickhoff, D., Waner, V., Bohling, Schwedler, S., Chrostowska, A., Daegelos, A., Maciejczyk, M., Stammmler, H-G., Neumann, B., *Dalton Trans.* **2011**, 40, 4334.
73. Kawanashi, Y., Muruyama, S., *J. Mater. Chem* **2002**, 12, 2245.
74. Ma, D., Chen, Z., Wang, Y., Wang, Y., Zhang, H., Fan, Y., Geo, H., Yao, D., Zhang, Y., Bi, H., Zhang, Z., *Inorg. Chem* **2009**, 48, 7230.
75. Montalti, M., Credi, A., Prodi, I., Gandolfi, M., T., *Handbook of Photochemistry*. 3 rd ed.; Taylor and Francis, Boca Raton, , 2006.
76. Kitamura, N., Saduka, E., Iwahashi, Y., Tsuge, K., Sasaki, Y., Ishizaka, S., *J. Phot. Photbio. Chem.* **2009**, 207, 102.
77. Chrostowska, A., Maciejczyk, M., Dargelos, A., Baylere, P. Weber, L., Werner, V., Eickhoff, D., Stammmler, H-G., Neumann, B., *Organometallics* **2010**, 29, 5192.
78. Schwedler, S., Eickhoff, D., Brockhinke, R., Cherian, D., Weber, L., Brockhike, A., *Phys. Chem. Cem. Phy.* **2011**, 13, 9301.
79. Lakowicz, J. R., Weber, G., *Biochemistry* **1973**, 12, 4161.
80. Steiner, R. F., Kirby, E.P., *J. Phys. Chem.* **1969**, 73, 130.
81. Knibbe, H., Rehn, D., Weller, A., *Ber Bunsenges Phys Chem* **1968**, 72, 257.

# Chapter Four

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## 4. Introduction

### 4.1 Synthesis of Boronic acid and their Esters

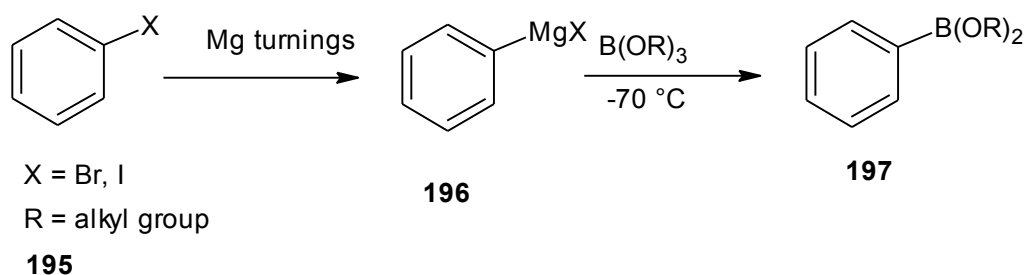
Arylboronic acid and their esters have been known for more than three decades yet their importance and versatility in organic synthesis are still recognised to date. Since their discovery in the early 1860s,<sup>1</sup> boronic acids and their esters have found a wide range of applications in different aspects such as synthetic intermediates in the preparation of biaryl compounds which are important structural components for various natural products, pharmaceutical compounds and biologically active compounds.<sup>2</sup> Boronic acids are also used as enzymes inhibitors,<sup>3</sup> as receptors and sensors for saccharides,<sup>4</sup> as well as bifunctional organic catalysts.<sup>5</sup>

The importance, versatility and the widespread applicability of boronic acids has demanded the development of efficient techniques for their synthesis. Through these developments, several methods have been discovered which make available a wide range of functionalised arylboronic acid and their esters with ease.<sup>6</sup> The following sections describe recent advances that have been achieved in the improvement of existing methods as well as the development of new routes to make available a large pool of functionalised aryl boronic acids.

#### 4.1.1 Metal-Halogen Exchange Method

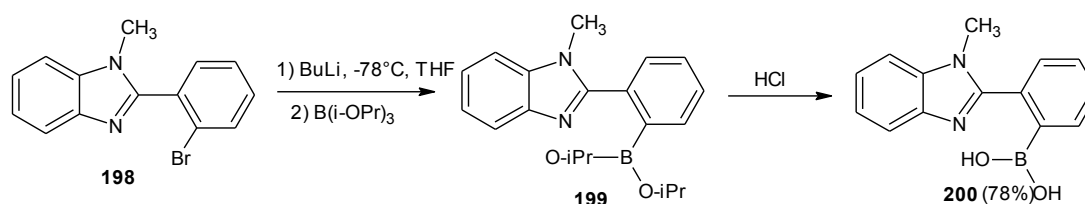
Metal-halogen exchange method is the oldest and the cheapest method to access boronic acids in reasonable yields. This method was discovered in the 1860s when a chemist, Frankland, reacted diethylzinc with triethylborate to produce triethylborane ( $\text{Et}_3\text{B}$ ), which upon oxidation in air, produced ethylboronic acid.<sup>1</sup> Building on the foundation described by Frankland, Melamed and co-workers reacted phenylmagnesium bromide with trimethylborate solution in their attempt to synthesise phenylboronic acid, however, this method provided the desired product in poor yields due to extensive formation of borinic acid side-products such as borinic derivatives.<sup>7</sup>

In order to avoid the formation of borinic side-products, Johnson and *et al.*<sup>8</sup> reported an improved procedure which involves the addition of phenylmagnesium bromide intermediate to a solution of tri-*n*-butylborate held at  $-70^{\circ}\text{C}$ . In the authors' point of view, the low temperature was intended to precipitate the nucleophilic phenylmagnesium bromide intermediate which eventually suppress its reactivity towards the formation of borinic acid side-products (**Scheme 55**).<sup>8</sup>



**Scheme 55**

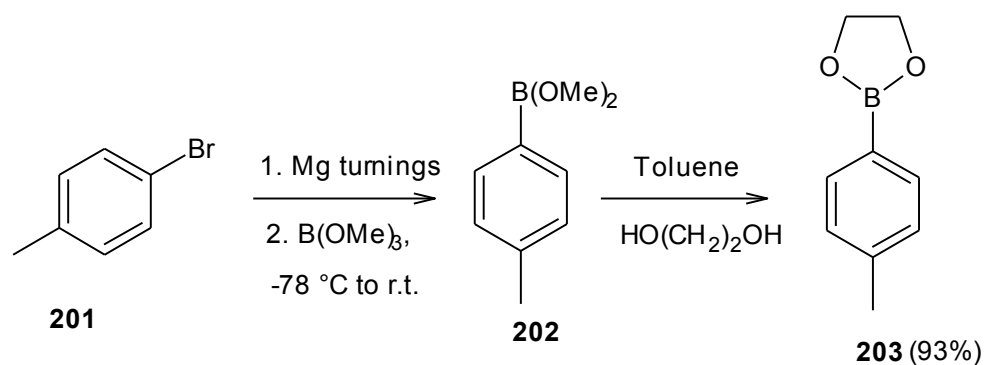
After this discoveries, this protocol has been successfully implemented in the synthesis of a range of boronic acids and their esters from the corresponding aryl halides.<sup>9</sup> This procedure leads to a mixture of magnesium salt, excess tri-alkylborate and the desired boronic ester.<sup>10</sup> To obtain free boronic acid, a standard workup procedure using a solution of an acid (usually 2M HCl) is required in order to hydrolyse the alkoxy leaving groups. Following the improved procedure, Blatch *et al.*<sup>11</sup> have successfully synthesised the intermediate boronic ester which upon acid hydrolysis furnished the desired free boronic acid in 78% yields (**Scheme 56**).<sup>11</sup>



**Scheme 56**

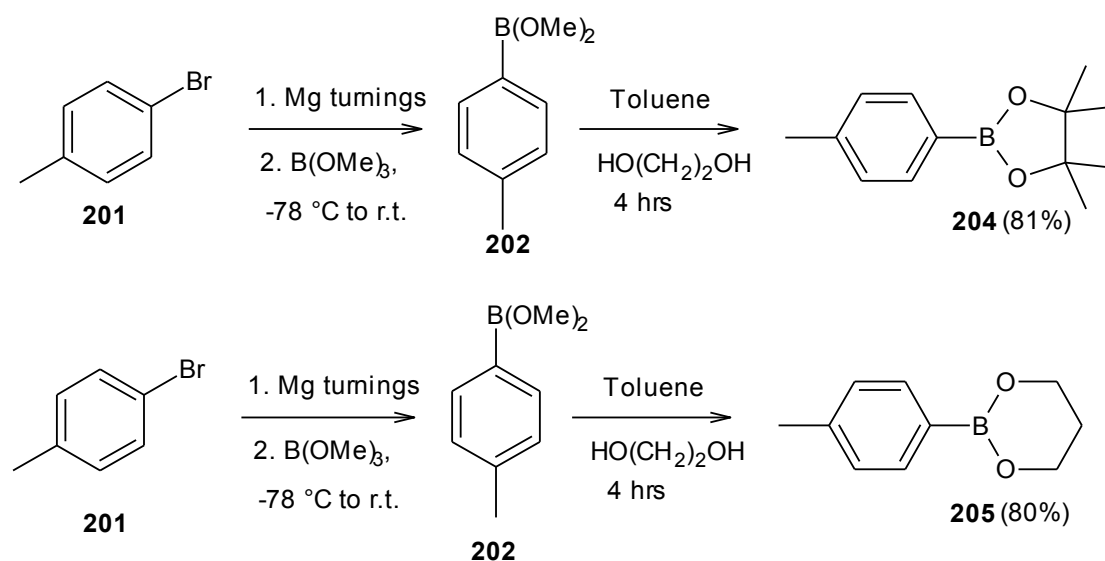
The drawback of the acid hydrolysis step is, however, that small water soluble boronic acids tend to dissolve in aqueous solution which in turn complicates the purification process and consequently leads to poor yields. To overcome these challenges, Wong and co-workers<sup>12</sup> disclosed an improved procedure which does not involve the aqueous workup step. In this approach, arylmagnesium bromide is treated

with an excess solution of trimethylborate at  $-78^{\circ}\text{C}$ . After 3 hr of stirring, the solvent and an excess trimethylborate solution were evaporated affording the crude product as white solid. The resulting white solid was heated under reflux in the presence of any 1,2-dialcohol compound in toluene affording the desired aryl boronic ester in excellent yields. (**Scheme 57**).<sup>12</sup>



**Scheme 57**

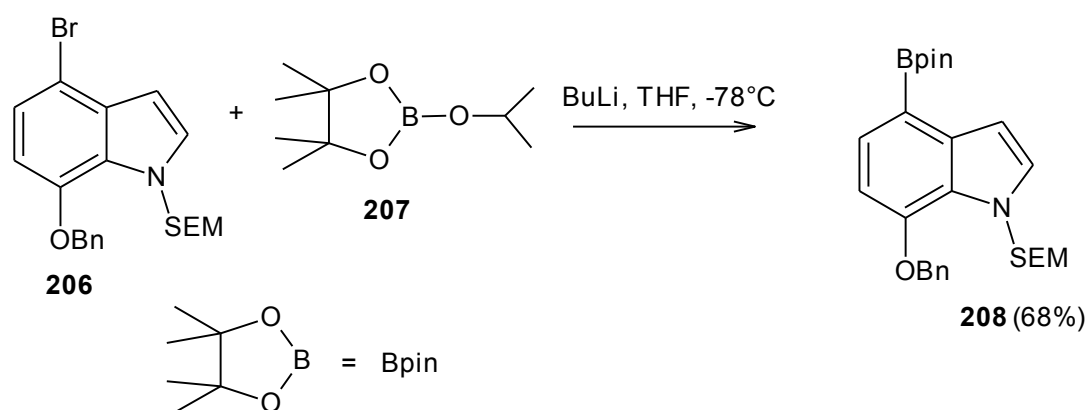
Several aryl-halides of markedly different structural features can be transformed into their corresponding arylboronic esters under these reaction conditions. This approach is not only limited to the use of ethylene glycol as a masking agent, other dialcohols such as pinacol and 1,3-propanediol can also be employed. For example, 2,4,6-trimethylboronic esters **204** and **205** were isolated in 81% and 80% yields from the related alcohols using the above-mentioned approach, respectively.<sup>12</sup>



**Scheme 58**



Although this procedure readily furnished the desired arylboronic esters after the cyclocondensation of the diol and the crude boronic acid, the evaporation of the solvent and an excess trimethylborate solution is untidy and laborious. An improvement to this procedure was reported by Garg and co-workers,<sup>13</sup> in which their improved method involved the *in situ* quenching of an aryl metal intermediate with pinacol borate ester. However, this method afforded the desired product in only moderate yields (**Scheme 59**).<sup>13</sup>



**Scheme 59**

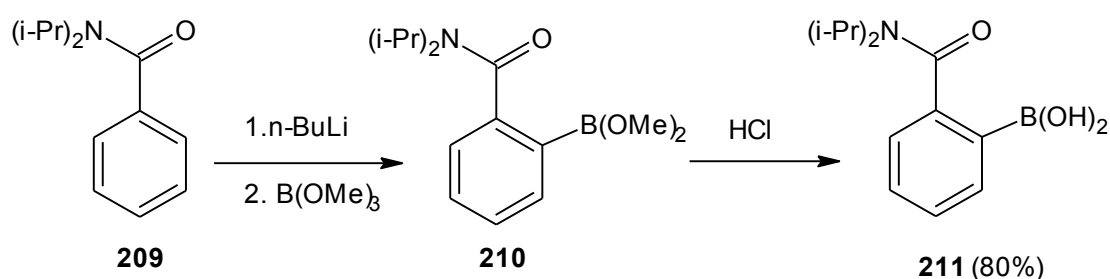
Although the metal-halogen exchange methodology provides a suitable protocol to access a large pool of boronic acids and their esters, this method is limited only to the use of halogenated aromatics. In addition, only expensive bromo- and iodo-functionalised aryl halides are frequently used, whereas easily accessible and low-cost chlorinated and non-halogenated arenes are not accommodated in these procedures.<sup>6</sup>

#### 4.1.1.1 Directed Ortho-Metallation

Alternatively, non-halogenated arenes could be transformed into their boronic acids provided they are functionalised with *ortho*-directing groups including amines, ethers and carbonyls. In this case, aryl compounds containing *ortho*-directing groups are treated with butyllithium at -78°C. The strong base (butyllithium) is intended to deprotonate the activated *ortho* position thus giving the *ortho*-aryllithium intermediate.<sup>6</sup> The resulting intermediate is subsequently quenched with trialkylborate

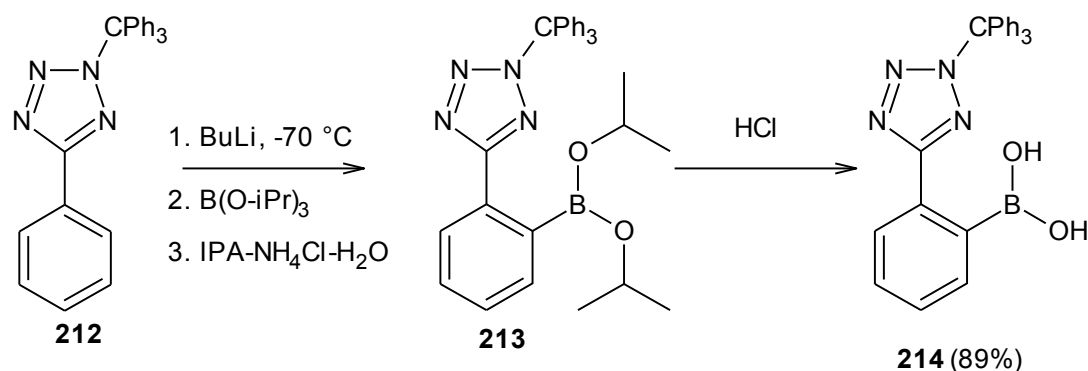
solution to give the corresponding alkylated arylboronate esters which, upon acid hydrolysis, provide the desired arylboronic acids in excellent yields.<sup>6</sup>

The efficiency of this protocol has been demonstrated by a number of research groups. Lauer and co-workers have successfully employed this procedure in their *ortho*-methylamino-phenyl boronic acid synthesis.<sup>14</sup> Sharp and Snieckus have also implemented this procedure in the preparation of *ortho*-carboxamido-phenylboronic acid (**Scheme 60**).<sup>15</sup>



**Scheme 60**

The reliability of the directed *ortho*-metallation method, in the preparation of boronic acids, is well demonstrated by its application in the pharmaceutical area where it has been shown to be a suitable method for the preparation of tetrazoleboronic acid, a precursor in the synthesis of the anti-hypertensive pharmaceutical drug Lasartan (**Scheme 61**).<sup>16</sup>



**Scheme 61**

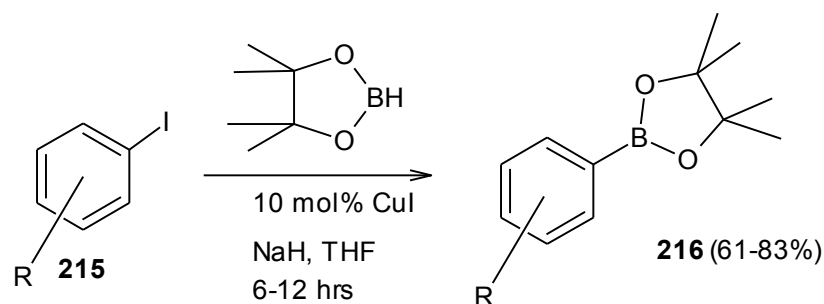
The successful implementation of metal-halogen and *ortho*-metallation methods in the synthesis of arylboronic acids greatly relies on the formation of the highly reactive

organomagnesium and organolithium intermediates.<sup>6</sup> These intermediates are well known for their air and moisture sensitivity which makes it a challenge to handle and manipulate them with ease.<sup>6</sup> In addition, these intermediates are highly nucleophilic making them incompatible with a variety of functional groups such as unprotected hydroxyl, amines and carbonyl groups. For these reasons, metal-halogen and *ortho*-metallation methods have found limited applications in the synthesis of arylboronic acid and esters functionalised with substituents which are sensitive towards nucleophilic attack.<sup>6</sup> Recently, various methods have emerged particularly metal-catalysed techniques, which make available a large pool of functionalised aryl boronic esters from their corresponding aryl halides, including the well known non-reactive aryl chlorides, in excellent yields.<sup>17</sup> Most of these methods employ an air and moisture stable pinacolborane which has also been demonstrated, with a number of experiments, to be thermally stable in most organic solvents.<sup>18</sup> In addition, pinacolborane has been shown to be more reactive whilst it is less prone to disproportionation when compared to catecholborane.

## 4.1.2 Metal-Catalysed Borylation methodologies

### 4.1.2.1 Copper-Catalysed Borylation Reactions

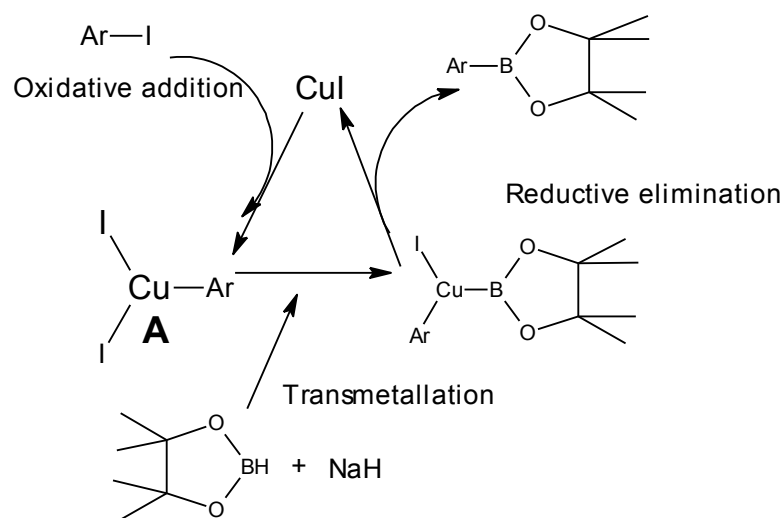
In 2006, Zhu and Ma<sup>19</sup> reported that pinacolborane couples smoothly with a range of aryl iodides in the presence of 10% CuI and NaH (as a base) at room temperature, to provide the coupled aryl boronate ester products in good yields. Initially, triethylamine was used as a base, however, no desired coupled-product was observed. According to the authors, the failure of this reaction was ascribed to the weak basicity of Et<sub>3</sub>N.<sup>19</sup> As a consequence, stronger bases such as <sup>t</sup>BuOK, Cs<sub>2</sub>CO<sub>3</sub> and NaHMDS were also examined; however, none of these bases gave the desired product in good yields. Excellent yields were reported when NaH was used; nonetheless, the authors did not give an explanation for this observed trend. A variety of aryl iodides with different substituents were transformed to their corresponding aryl boronate esters in 61-83% yields under these optimised reaction conditions (**Scheme 62**).<sup>19</sup>



R = Ph, OMe, CF<sub>3</sub>, *t*-BuO<sub>2</sub>C, OH

### Scheme 62

To account for the coupling reaction, Zhu and Ma proposed a mechanism which closely resembles the catalytic cycle suggested for Ullmann and Miura-Masuda type coupling reactions (**Figure 49**). In the mechanism, the carbon-iodide bond of an aryl iodide is oxidatively added to the CuI centre affording Cu(III) intermediate **A**.<sup>19</sup> This step is followed by the deprotonation of pinacolborane which subsequently facilitates the transmetalation of the deprotonated species to the metal centre. Finally, the reductive elimination step releases the desired coupled-aryl boronate ester and regenerates the catalyst for another cycle (**Figure 49**).<sup>19</sup>



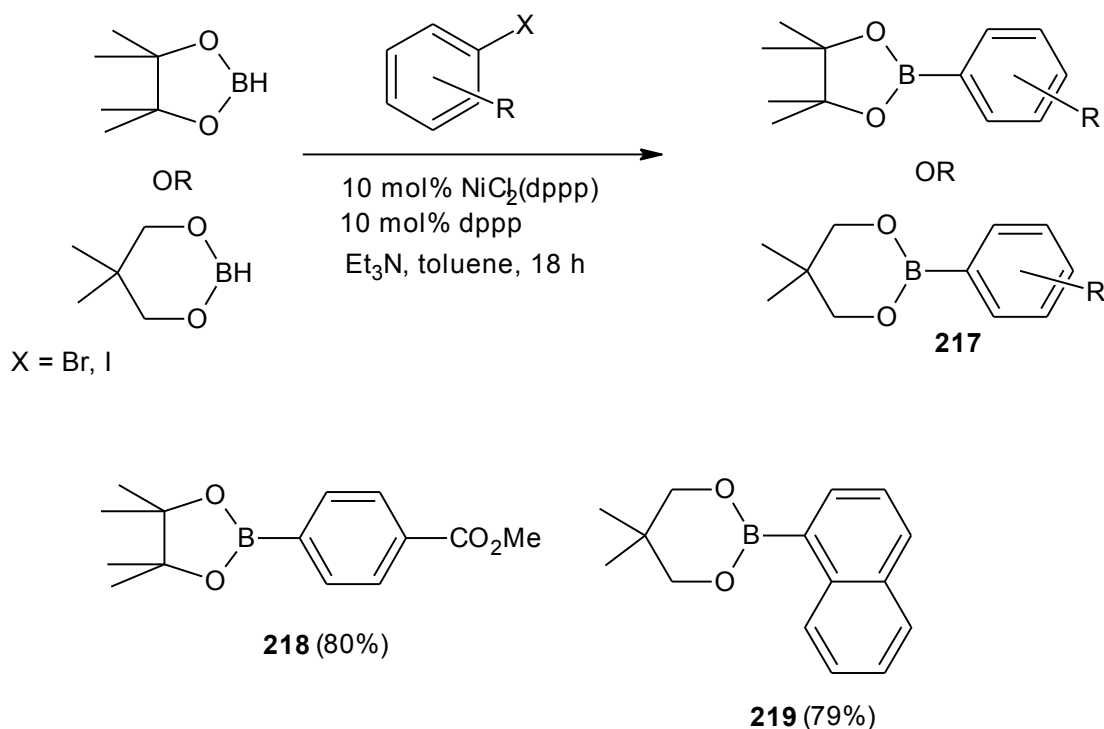
**Figure 49: pinacolboronylation of iodobenzene**

Although this method provides an easy and a milder route for the conversion of aryl iodides to their corresponding arylboronate esters, this protocol is only limited to the use of more reactive iodoarenes. Aryl bromides were demonstrated to be unsuitable electrophiles under these reaction conditions. A modification to this procedure was

reported by Rosen and co-workers<sup>20</sup> in their nickel-catalysed pinacolborylation and neopentylglycolborylation of aryl bromides and iodides.

#### 4.1.2.2 Nickel-Catalysed Borylation Reactions

According to Rosen *et al.*<sup>20</sup> the treatment of pinacolborane or neopentylglycolborane with aryl bromide or iodide in the presence of a catalytic amount of  $\text{NiCl}_2(\text{dppp})$  and triethylamine as a base in refluxing toluene furnished, after the purification step, the desired esters in excellent yields (**Scheme 63**).



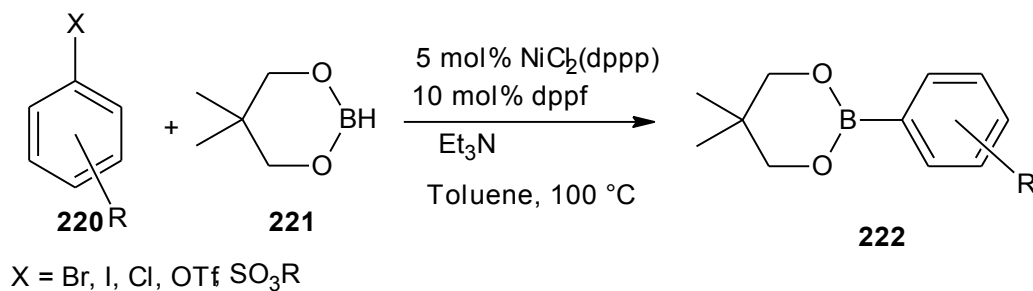
**Scheme 63**

Attempts to use aryl chlorides as electrophiles failed to give the corresponding arylpinacolborate esters. This observation was, as it is well documented in the literature, ascribed to slow oxidative addition to the metal of the carbon-chlorine bond.<sup>20, 21</sup> The solution to these challenges was recently reported by Moldoveanu *et al.*<sup>22</sup> and Knochel *et al.*<sup>23</sup> with the use of the nickel catalyst with mixed ligands, especially  $\text{NiCl}_2(\text{dppp}^{\text{c}})/\text{dppf}^{\text{d}}$ , which significantly improves the efficiency of the nickel-catalysed neopentylglycolborylation reaction. With this new system, a variety

<sup>c</sup> Dppp: 1,3-Bis (diphenylphosphino)propane

<sup>d</sup> Dppf: 1,1'-Bis (diphenylphosphino) ferrocene

of aryl chloride, even the less reactive aryl sulfonates,<sup>24</sup> were smoothly neopentylglycolborylated to the corresponding aryl neopentylglycolboronate esters (**222**) in less than 72 hr (**Scheme 64**).<sup>22, 23</sup>

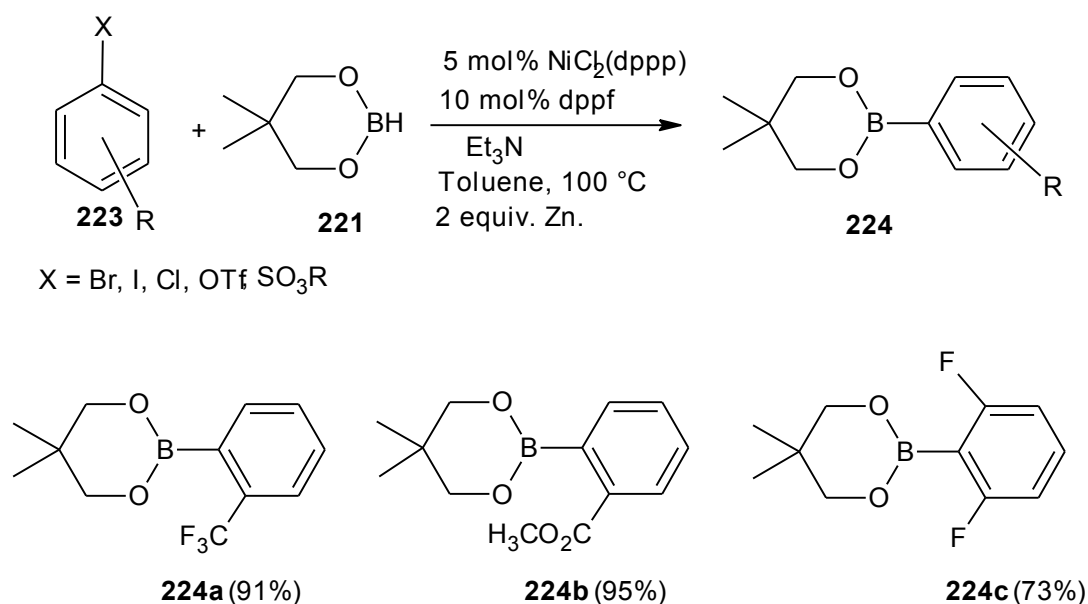


**Scheme 64**

The use of mixed ligands to accelerate the nickel-catalysed neopentylglycolborylation reactions was a great contribution to the development of nickel-catalysed borylation reactions. In addition to its effectiveness, Moldoveanu and co-workers<sup>25</sup> have recently reported that this methodology is also a superior protocol for the neopentylglycolborylation of *ortho*-substituted aryl halides (a reaction which has been describe on many occasions to be unsuccessful) with the aryl iodides reaching maximum conversion in few hours, whereas aryl bromide and chloride counterparts required longer reaction times.<sup>25</sup>

The desire to improve the nickel-catalysed neopentylglycolborylation was recognised by Leowanawat and *et al.*<sup>26</sup> when they realised that this transformation takes an unnecessarily longer time to completion, which in turn, has been reported to facilitate the formation protodeborated side-products. As a result, the group developed an improved zero-valent metal activated neopentylglycolborylation procedure. In this case, aryl halides are neopentylglycolborated under normal neopentylglycolborylation conditions except that a small amount of zero-valent metals such as Zn, Al, Ca and Mg are added to the reaction mixture.<sup>26</sup> The addition of these metals to the reaction mixture has been reported to greatly accelerate the neopentylglycolborylation reaction and also improves the yields of the desired products. Due to the limited mechanistic studies on the nickel-catalysed neopentylglycolborylation in the literature, the authors were unable to rationalised the role of these metals in accelerating the reaction rate.<sup>26</sup>

However, they tentatively presume that these metals reduce the Ni(II) pre-catalyst to its active form which in turn facilitates the oxidative addition of the aryl halide to the metal centre. With these modifications, the less reactive *ortho*-substituted aryl chlorides and bromides, which were previously reported to require more than 72 hr for moderate conversion, were borylated in less than 1 hour in excellent yields (**Scheme 65**).<sup>26</sup>

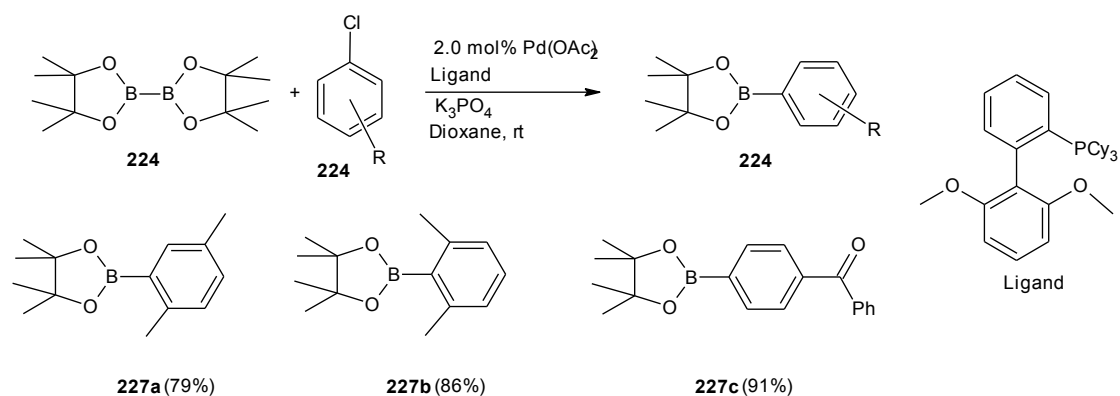


**Scheme 65**

#### 4.1.2.3 Palladium-Catalysed Borylation Reactions

Palladium catalysts have also been shown to affect the borylation reaction of arenes in the presence of triethylamine as a base. In 2004, Broutin and *et al.*<sup>27</sup> reported an efficient Pd-catalysed transformation of functionalised aryl bromides to their pinacolboronate esters in moderate to good yields.<sup>27</sup> Murata *et al.*<sup>28</sup> on the other hand have confirmed the efficiency of this methodology when they successfully employed this protocol in the pinacoloborylation of a range of aryl halides. However, in their original report it was pointed out that even though good yields of the desired pinacolborylated products are obtained using this method, this procedure is only suitable for the pinacolborylation of aryl iodides and bromides, whereas easily accessible and cost effective aryl chlorides are not reactive under these reaction conditions.<sup>28</sup>

Billingsley and co-workers<sup>18</sup> subsequently released a report which describes the pinacolborylation of aryl chlorides in the presence  $\text{Pd}(\text{OAc})_2$  as a catalyst. According to these authors the treatment of aryl chloride with bis-(pinacolato)diboron under the influence of  $\text{Pd}(\text{OAc})_2$ , potassium acetate and dialkylphosphinobiphenyl ligand, furnished the expected pinacolborylated aryl esters in high yields (**Scheme 66**).<sup>18</sup>

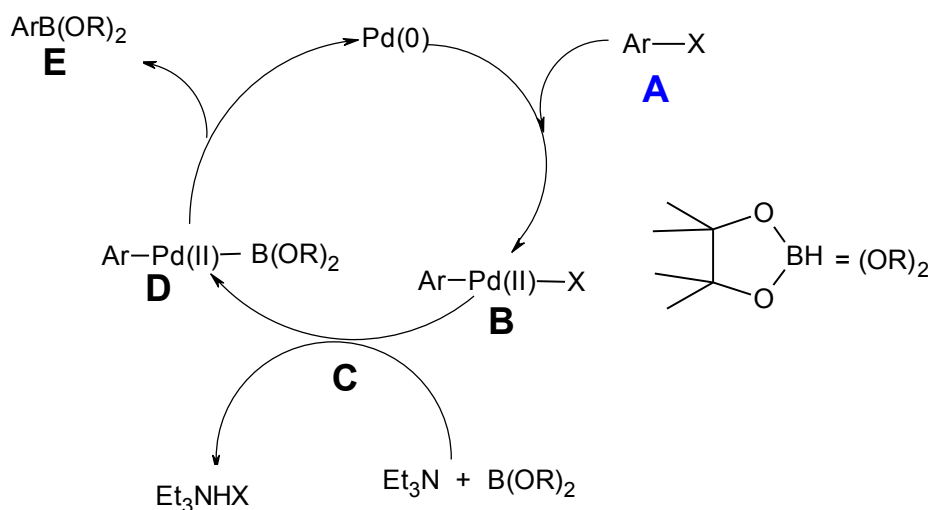


**Scheme 66**

In 2008, Billingsley and *et al.* further extended their studies to the borylation of aryl halides with pinacolborane. In this study, a range of aryl halides with markedly different structures were smoothly converted to their corresponding aryl pinacolborate esters using  $\text{PdCl}_2(\text{CH}_3\text{CN})_2$  as a catalyst.<sup>29</sup>

To account for the palladium-catalysed borylation of aryl halides in the presence of triethylamine as a base, Ishiyama and Masuda independently proposed the same mechanism (**Scheme 67**). In their proposal, the carbon-halide bond of an electrophile **A** oxidatively adds to the zero-valent Pd metal to form  $\text{Ar-Pd(II)-X}$  adduct **B**, which immediately reacts with a pinacolborane ion (formed from the deprotonation of pinacolborane) to generate  $\text{Ar-Pd(II)-B(OR)}_2$  intermediate **D**. The desired product **E** is reductively eliminated from the Pd(II) centre in order to regenerate Pd(0) species for the next catalytic cycle (**Scheme 67**).





**Scheme 67**

The development of simple, efficient, economically viable, mild and highly yielding protocols for the synthesis of boronic acids and their esters is clearly indicative of the importance of these species in organic chemistry.<sup>30</sup> Certainly, boronic acids and their corresponding esters have long been known and have been demonstrated to be the most valuable nucleophilic coupling partners in the transition metal-catalysed carbon-carbon bond constructions.<sup>31</sup>

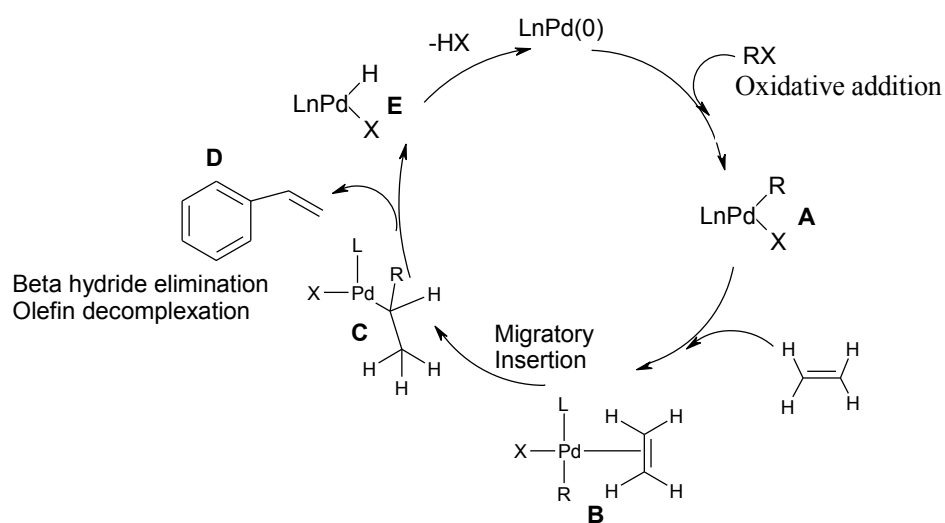
The transition metal-mediated cross-coupling reactions for the construction of carbon-carbon bonds, specifically the preparation of biaryls compounds, have emerged as one of the most powerful and versatile methodologies in organic synthesis. Biaryls are important structural components and are also precursors for the synthesis of natural products,<sup>32</sup> pharmaceutical compounds,<sup>33</sup> functional materials, polymers and agrochemical intermediates.<sup>34</sup> The significance of biaryls in organic synthesis has attracted considerable attention for the developments of new methods which make possible the formation of  $\text{C}_{\text{aryl}}\text{-C}_{\text{aryl}}$  bonds. As a consequence, numerous transition metal-mediated methods for the construction of  $\text{C}_{\text{aryl}}\text{-C}_{\text{aryl}}$  bonds have been developed and implemented such as Heck, Stille and Suzuki-Miyaura cross-coupling reactions.

## 4.2 Cross-Coupling Reactions

### 4.2.1 Heck Cross-Coupling Reaction

Heck<sup>35</sup> was the first to discovered in 1968, that the treatment of an olefins with an *in-situ* generated phenylpalladium halide intermediates provided styrenes, through a  $\beta$ -hydride elimination process, in good yields (Scheme 4.15).<sup>36</sup> The discovery of this protocol provided an efficient procedure for the arylation of olefins at room temperature. To get an accurate and deep understanding of this reaction, Heck proposed a mechanism in which the organohalide is oxidatively added to the Pd (0) centre. This effect formally changes the oxidation state of the palladium metal from Pd(0) to Pd(II) which, in turn, leads to the formation of the organopalladium intermediate **A** (Scheme 68).<sup>37</sup>

The coordination of olefins to the palladium centre produces intermediate **B** which, during the migratory insertion step, rearranges in such a way that a new palladium–carbon bond is formed thus giving complex **C**. The desired coupled-product **D** is released from the metal centre through the process called  $\beta$ -hydride elimination or olefin decomplexation. To regenerate the active Pd(0) for the next catalytic cycle, the short-lived intermediate **E** is reduced by losing the HX moiety thus changing Pd(II) to the active Pd(0) complex (Scheme 68).<sup>37</sup>

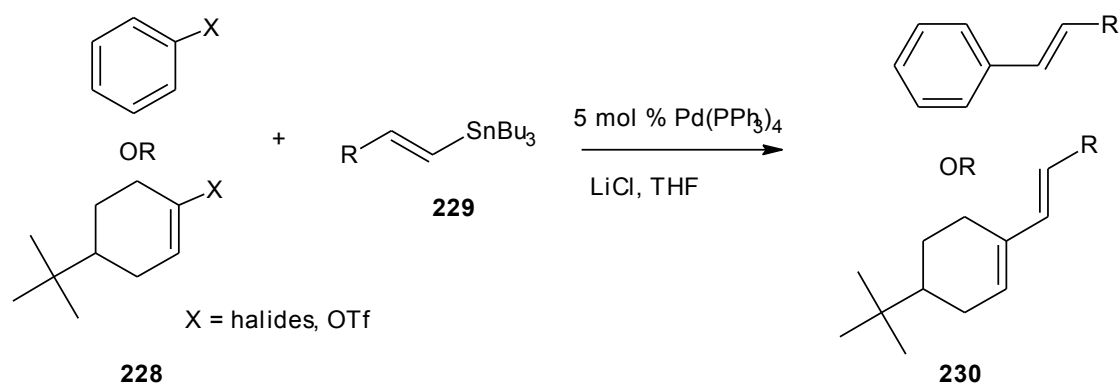


Scheme 68

After these reports by Heck, the Heck cross-coupling reaction became a popular method for the arylation of olefins in organic synthesis. A number of olefins with markedly different structures and steric requirements were demonstrated to be suitable nucleophiles under the reported reaction conditions.<sup>38</sup>

#### 4.2.2 Stille Cross-Coupling Reaction

In 1979, Stille and co-workers documented, in a series of papers, that the reaction of organostannanes with alkenyl and aryl halides or triflates, in the presence of Pd(0) as a catalyst, led to the formation of new carbon-carbon bonds between the two organic moieties (**Scheme 89**).<sup>39</sup>



**Scheme 68**

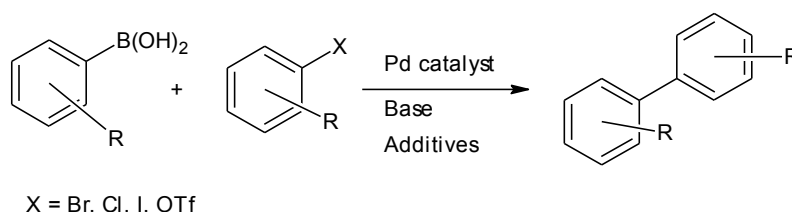
Since its discovery, this methodology has been applied in the synthesis of several vinyl and aromatic compounds and has emerged as one of the most popular in the construction of carbon-carbon bonds.<sup>40</sup> Although Stille cross-coupling reactions have emerged as one of the powerful transition metal-catalysed carbon-carbon bond forming methodologies, the difficulties encountered during the purification of the desired products and the toxicity of tin by-products has presented a barrier for the application of this protocol in the synthesis of pharmaceutical and natural products.<sup>40</sup>

Alternatively, the transition metal-mediated carbon-carbon bond formation can also be achieved with the use of organoboron compounds as nucleophilic coupling partners.<sup>41</sup> This reaction, formally known as the Suzuki-Miyaura cross-coupling reaction, has become the most versatile in organic synthesis, particularly, because of 1) the ease with which the organoborane compounds are obtained, 2) the degradation

of these species into the environmentally friendly boric acid, 3) the mildness of the reaction conditions which in turn allows for the tolerance of numerous functional groups, and finally, 4) the general applicability of the reaction conditions.<sup>42</sup>

### 4.2.3 The Suzuki-Miyaura Cross-Coupling Reactions

The Suzuki-Miyaura cross-coupling reaction was discovered in 1979 by Suzuki and co-workers when they observed that substituted alkenyl and arylboronic acid and their corresponding esters are coupled with organic halides or triflates in the presence of palladium catalyst and a base at elevated temperatures (**Scheme 70**).<sup>43</sup> After these discoveries, several arylboronic acid and their esters with markedly different structures and steric requirements were reacted with a range of aryl halides in the presence of different palladium/ligand combination in order to assess the scope and limitations of this methodology.<sup>44</sup>



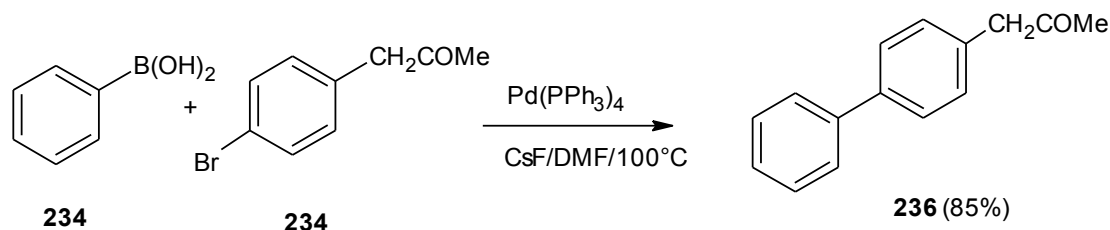
**Scheme 70**

A lot of effort in the Suzuki cross-coupling reaction has, in the past decade, been concentrated towards the development of new procedures that promote the cross coupling and broaden the scope of the reaction.<sup>45</sup> Through these efforts, tremendous progress has been achieved towards effective ligands,<sup>46</sup> solvents, bases, polymer-bound palladium catalyst and recently the use of nickel catalysts that enhances the efficiency of this cross-coupling reaction.<sup>47</sup>

In the following sections attention is focused on the progress that has recently been achieved in the improvement of the Suzuki-Miyaura cross-coupling reactions. Initially, the advancement and the current research focus on the palladium mediated Suzuki cross-coupling will be looked at, this section will be followed by the nickel catalysed cross-coupling counts

### 4.3.1 The Palladium Catalysed Suzuki-Miyaura Cross-Coupling Reactions

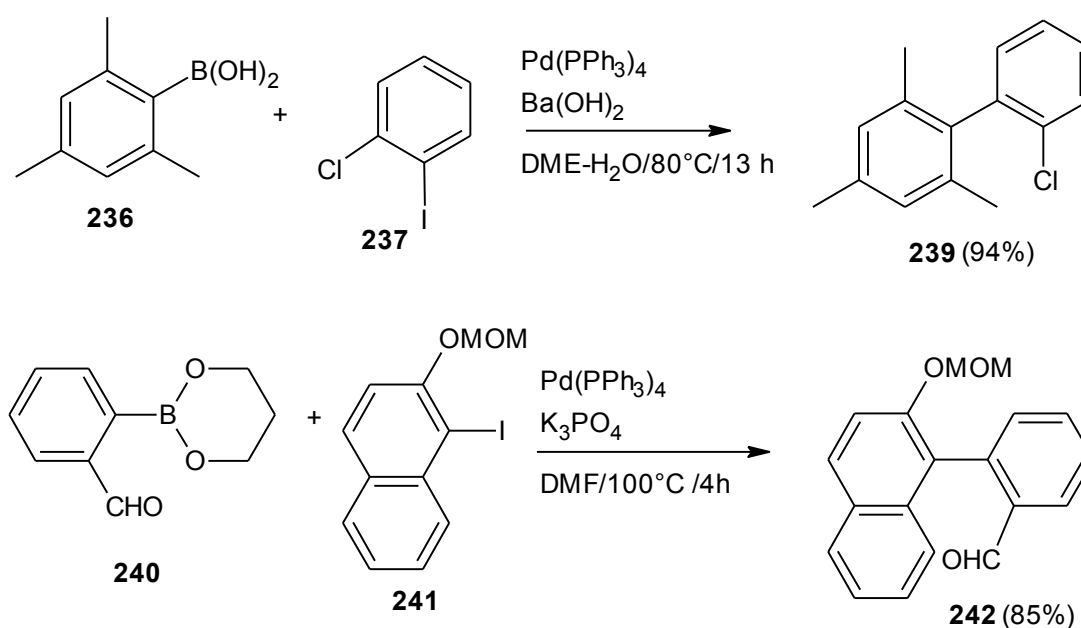
The first protocol for the synthesis of biaryls reported by Suzuki made use of an aqueous sodium carbonate, triphenylphosphine and benzene as base, catalyst and solvent, respectively.<sup>48</sup> Under these reaction conditions, phenylboronic acid was coupled with a range of aryl bromides and iodides giving the corresponding coupled-products selectively in moderate to good yields.<sup>48</sup> After this report, different advancements were made in order to enhance the efficiency of the Suzuki cross-coupling reaction. For example, Wright *et al.* reported in 1994 that the reaction of phenylboronic acid with the brominated arene proceeded successfully under the influence of a catalytic amount of  $\text{Pd}(\text{PPh}_3)_4$  in the presence of CsF and DME as a base and a solvent, respectively (**Scheme 71**).<sup>49</sup>



**Scheme 71**

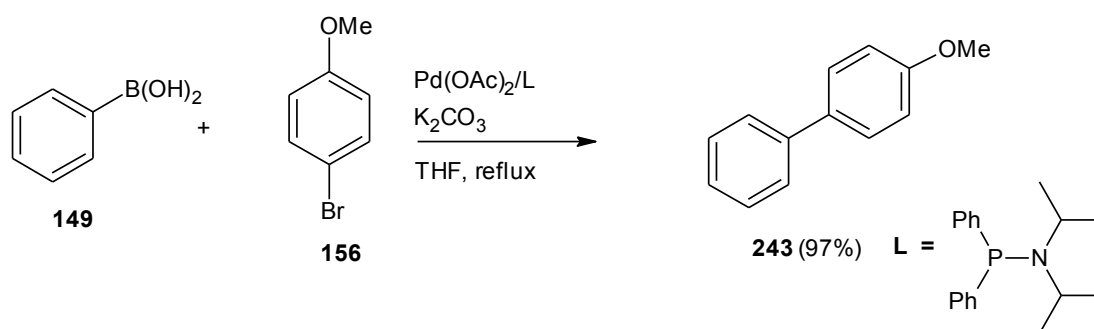
Sterically hindered boronic acids and their esters substituted at the 2-position or functionalised with electron-withdrawing substituents are usually poor nucleophilic coupling partners due to either the steric hindrance or susceptibility to hydrolytic deboration. To overcome these difficulties, Watanabe and co-workers made use of  $\text{Ba}(\text{OH})_2$  and  $\text{K}_3\text{PO}_4$  as bases (**Scheme 72**).

According to the authors, these strong bases are crucial for the cross-coupling reaction of sterically hindered nucleophilic coupling partners as they increases the electrophilicity of the organic group attached to the boron atom, therefore, accelerating the transtallation process.<sup>50</sup>



**Scheme 72**

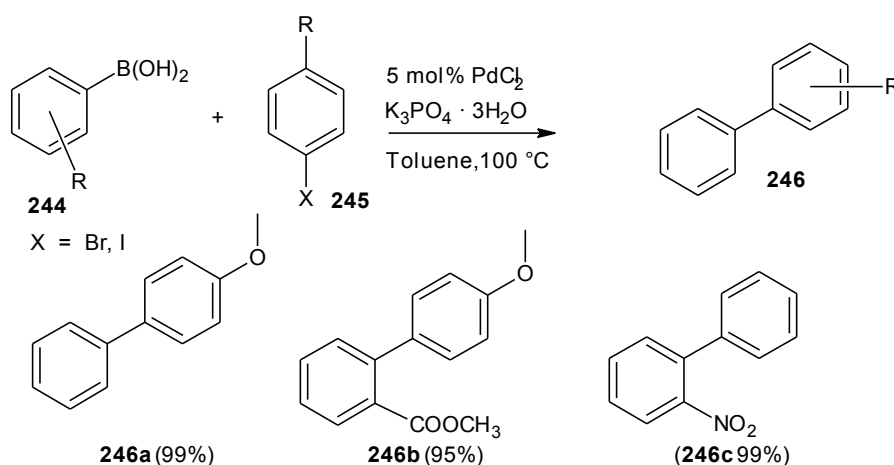
The observation made by Watanabe and *et al.* was also confirmed by Zhang and Chan,<sup>51</sup> in 1996, when they realised the remarkable effect of using strong bases in the cross-coupling reaction of sterically bulky arylboronic acids. Zhang and Chan reported that in the presence of a strong base such as potassium *t*-butoxide, *ortho*-disubstituted boronic acids are smoothly coupled with aryl halides without any by-products being formed.<sup>51</sup> Stronger inorganic bases such as TIOH or  $\text{Ti}_2\text{CO}_3$  are usually toxic or are usually moisture and air sensitive in the case of BuLi or potassium *t*-butoxide, which consequently limits the applicability of these protocols in the preparation of substituted biaryls industrially.<sup>52</sup> Interested in the development and the improvement of the Suzuki cross-coupling reaction conditions, Cheng *et al.* investigated, in 2003, the effect of electron-rich phosphine based-ligands on the rate of the cross-coupling reactions.<sup>53</sup> Their results revealed that the treatment of phenylboronic acid with aryl bromides in the presence of electron-rich ligands accelerate the cross-coupling reaction yielding the coupled-products in excellent yields (**Scheme 73**). The authors reported that the electron-rich ligands accelerates the oxidative addition step which in turn facilitates the oxidation of the palladium metal making it easier for the carbon–halogen bond to be added to the metal centre.<sup>53</sup>



**Scheme 73**

The remarkable impact of the ligands in the improvement of the Suzuki cross-coupling reaction was further demonstrated by Bellina *et al.*<sup>54</sup> when they reported that the use of N- and P-based-ligands dramatically increases the efficiency of the Suzuki-Miyaura cross-coupling reaction. Even though the addition of the ligands has been reported, by several authors, to enhance the effectiveness of the Suzuki cross-coupling, most of these ligands are costly, air sensitive, they complicate the workup procedures as well as the purification of the desired products, which in turn significantly limits the widespread applicability of these procedures in the large scale production of biaryls.<sup>55</sup>

To overcome these obstacles, the Pan group<sup>55</sup> and several other researchers<sup>56, 57</sup> have recently developed and implemented the ligand-free Suzuki cross-coupling procedure for the synthesis of symmetrical and asymmetrical biaryls.<sup>58</sup>



**Scheme 74**

Pan *et al.*<sup>55</sup> demonstrated that the reaction of phenylboronic acids substituted with either the electron-withdrawing or electron-donating functionalities with aryl bromides and iodides proceeded, with great ease, in the presence 5 mol% PdCl<sub>2</sub> as a catalyst furnishing the desired coupled-products in yields of up to 99% (**Scheme 74**).<sup>55</sup> The ligandless Suzuki cross-coupling protocol has also been demonstrated recently by the Andrio group to be highly efficient for the preparation of both substituted and unsubstituted biaryls.<sup>57</sup> In this case, the treatment of the aryl boronic acid with aryl bromides, under the influence of 1 mol % Pd(OAc)<sub>2</sub>, affords the coupled-products in yields greater than 80% within 10 minutes.

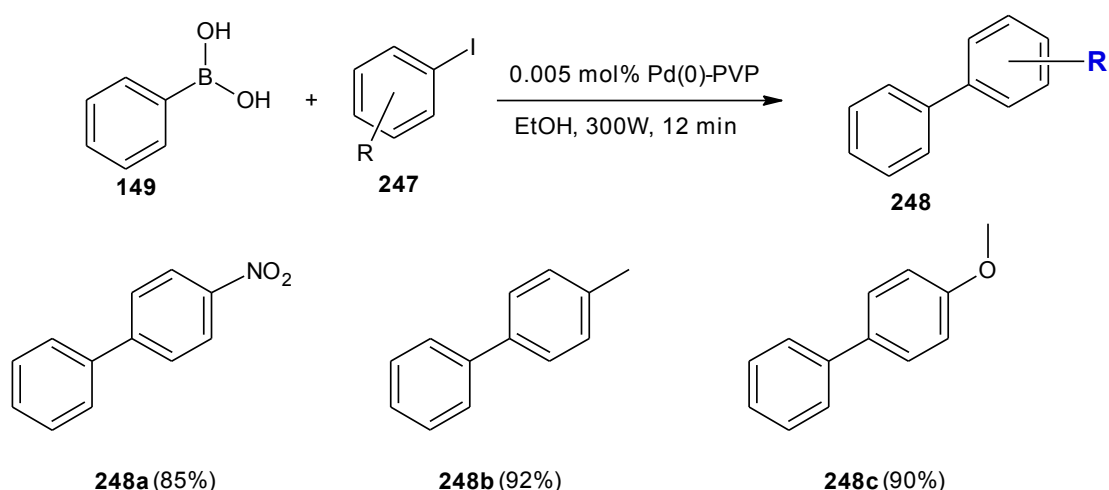
Current research on the Suzuki cross-coupling arena has been devoted at the development and the application of palladium nanoparticles as the potential cross-coupling catalysts.<sup>59</sup> The use of nanoparticles in catalysis has been described to be advantageous (compared to the use of bulk catalysts) due to their increased surface area and their easy recovery allowing for better catalytic activity and multiple usage of the catalyst.<sup>60</sup> The application of nanoparticles in catalysis has attracted considerable attention for improvement and as consequence, several research groups have directed their research focus at investigating the scope and limitation of these newly discovered molecules.<sup>61</sup>

For instance, the Martins group has reported the use of Pd(0)-PVP nanoparticles in the preparation of biaryls. According to the authors, aryl boronic acids are efficiently coupled with aryl iodides in the presence of 0.005 mol% Pd(0)-PVP<sup>c</sup> catalyst and K<sub>2</sub>CO<sub>3</sub> base under the microwave irradiation furnishing the desired products in only 12 minutes (**Scheme 75**).<sup>60</sup>

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<sup>c</sup>PVP : poly(*N*-vinyl-2-pyrrolidone)





**Scheme 75**

In a related study, Lorenzo<sup>62</sup> recently (2012) investigated the influence of the size and shape of Pd nanoparticles on the efficiency of the Suzuki cross-coupling reaction. He and other research groups found that the rate of the catalytic activity increases with a decrease in the particles size. This behaviour was ascribed to their high surface-to-volume ratio which in turn increases the reaction site.<sup>62</sup>

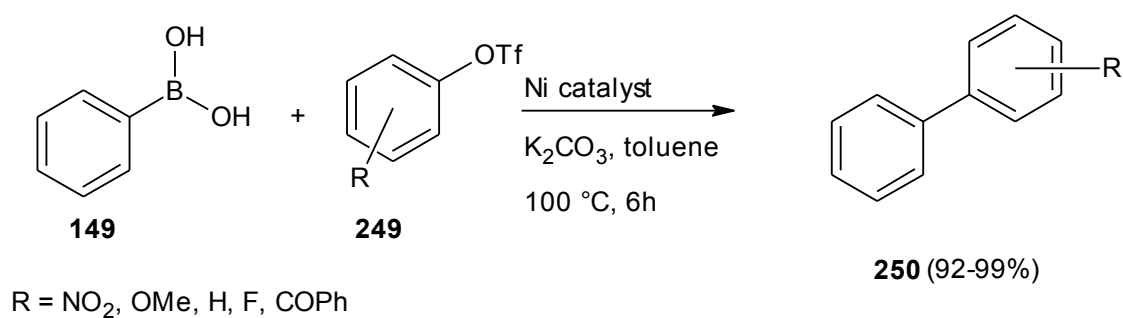
A vast number of palladium catalysts have been reported to mediate the Suzuki cross-coupling reaction in the literature. Palladium catalyst with bulky triphenylphosphine ligands such as Pd(PPh<sub>3</sub>)<sub>4</sub> and Pd(PPh<sub>3</sub>)<sub>2</sub> are commonly used in the Suzuki cross-coupling reaction because of their stability towards prolong heating. Ligandless palladium catalyst such as Pd(OAc)<sub>2</sub> and PdCl<sub>2</sub> have also been reported to be effective since they are more reactive and insensitive to air and moisture.

### 4.3.2 Nickel Catalysed Suzuki Cross-Coupling Reactions

The palladium-catalysed Suzuki cross-coupling reaction is one of the most efficient methodologies for the formation of aryl-aryl bonds. Tremendous progress in the development of various Pd catalyst has been achieved allowing the cross-coupling of aryl halides (including previously non-reactive aryl chlorides) with arylboronic acid to be highly efficient even under mild reaction conditions.<sup>48</sup> Even though this method has proven highly successful in the preparation of substituted biaryls, the high cost of both the Pd catalyst and the supporting ligands demanded an alternative protocol for the preparation of biaryls. Indeed, the longstanding search for a cheap, easily available and a highly reactive catalyst conducted by Percec and co-workers soon

revealed the effectiveness of nickel catalysts as an alternative to the mostly used Pd catalysts.<sup>63</sup>

In 1995, the Percec group reported, for the first time, the use of nickel catalyst in the Suzuki cross-coupling reaction.<sup>63</sup> Since this first report by Percec, several different nickel-based catalysts<sup>64-68</sup> have been reported to mediate the Suzuki cross-coupling reaction of aryl halides including previously non-reactive aryl chlorides<sup>69</sup> and aryl mesylates<sup>70</sup> under mild reaction conditions.<sup>70</sup> For instance, Fan *et al.*<sup>71</sup> have reported the application of easily accessible Ni(II)-(σ-aryl) complexes as the catalyst for the Suzuki cross-coupling reaction. Fan *et al.*<sup>71</sup> documented that the reactions of substituted aryltosylates with aryl boronic acids proceeded smoothly in the influence of a catalytic amount of Ni(PPh<sub>3</sub>)<sub>2</sub>(1-naphthyl)Cl and K<sub>2</sub>CO<sub>3</sub> as a base providing the desired product in excellent yields (**Scheme 76**).<sup>71</sup>



**Scheme 76**

## **4.4 Aims of Chapter Four**

Although palladium-catalysed Suzuki-Miyaura cross-coupling reaction is a well established methodology for the preparation of substituted biaryls, this method is dependent exclusively on the use of aryl boronic acids as nucleophilic coupling partners. There are only few publications in the literature which have reported the use of other organoborane derivatives that could be used in the Suzuki-Miyaura cross-coupling reaction. To the best of our knowledge, 2-arylbenzo-1,3,2-diazaborole derivatives have never been described in the cross-coupling reaction despite their profound Lewis acidity and stability which are advantageous during the transmetalation step.

The main objectives of this project are:

1. To improve the Suzuki-Miyaura cross-coupling reaction by expanding the scope of organoborane compounds to ultra-stabilised 2-arylbenzo-1,3,2-diazaborole as coupling partners.
2. To evaluate the potential suitability of these compound as the Suzuki coupling partner by reacting them with a range of aryl bromides bearing electron-withdrawing and electron-donating functionalities, in the preparation of substituted biphenyls
3. To compare yields of substituted biphenyls obtained using aryl boronic acids to those obtained using 2-arylbenzo-1,3,2-diazaborole as coupling partners.

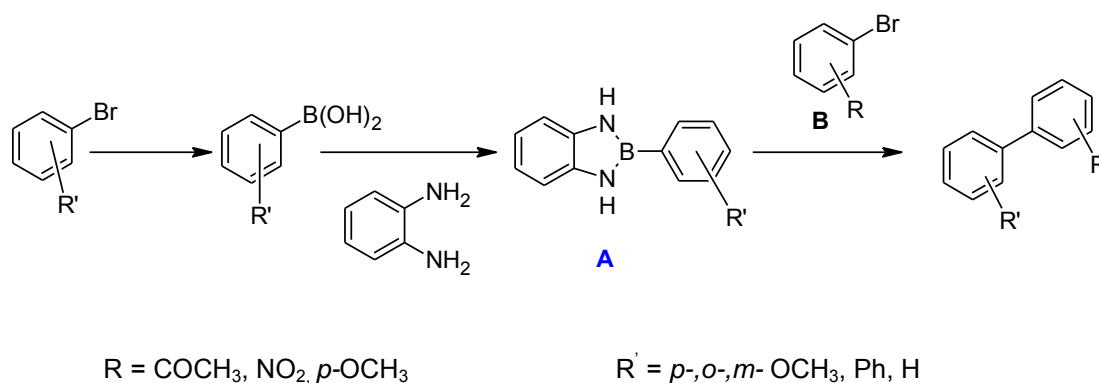
## 4.5 Results and Discussion

### 4.5.1 Preface

In chapter two, attention was directed at investigating the suitability of 2-alkyl/alkenylbenzo-1,3,2-diazaborole compounds as Suzuki coupling partners. It was found that these compounds are not only stable towards air and moisture when compared to the oxygenated analogues, but are also remarkable Suzuki coupling partners furnishing the desired coupled-product in excellent yields in or less than 20 minutes.

In chapter three, a lot of attention has been devoted to the assessment of the bonding parameters between the boron and the surrounding atoms in order to evaluate the charge density around the boron atom. From these studies, it was found that the intriguing properties displayed by 2-arylbenzo-1,3,2-diazaborole compounds are due to the enhanced  $\pi$ -interaction between the vacant  $2p_z$ -orbital on the boron atom and the  $\pi^*$ -orbital on the attached organic  $\pi$ -system. This enhanced  $\pi$ -interaction between the diazaborolyl group and the aromatic ring increases the charge density around the boron atom which in turn is believed to weaken the boron-carbon bond thus facilitating the transmetalation step during the cross-coupling processes.

This chapter is focused on the evaluation of the synthesised 2-arylbenzo-1,3,2-diazaborole compounds as potential Suzuki coupling partners. This evaluation will be achieved by reacting 2-arylbenzo-1,3,2-diazaborole compounds with various aryl bromides bearing either electron-withdrawing or electron-donating functionalities under the Suzuki cross-coupling reaction conditions (**Scheme 77**).



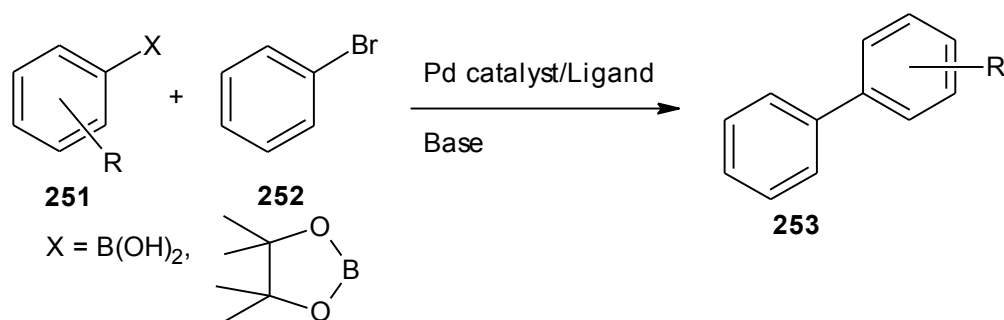
**Scheme 77**

The synthesis of the starting materials (arylboronic acids and 2-arylbenzo-1,3,2-diazaboroles) are covered in details in chapter three and will therefore not be duplicated in this chapter. In the section that follows, attention will be focused on the preparation of either symmetrical or non-symmetrical biaryls using 2-arylbenzo-1,3,2-diazaborolane compounds as nucleophilic coupling partners.

### 4.5.2 The Suzuki-Miyaura Cross-Coupling Reaction.

The carbon-carbon bond formation reactions have become one of the most important processes in organic chemistry.<sup>72</sup> One of these processes is the palladium-catalysed Suzuki-Miyaura cross-coupling reaction, which has become the most popular methodology for the construction of the carbon-carbon bonds of biaryls. The Suzuki-Miyaura cross-coupling reactions have proven to be the most efficient, versatile and frequently used transition metal-catalysed cross-coupling reactions for the preparation of both the symmetrical and asymmetrical biaryls,<sup>41</sup> which themselves have found diverse applications as liquid crystals, chiral ligands, structural components of pharmaceuticals,<sup>33</sup> natural products<sup>32</sup> and herbicides.<sup>73</sup>

The non-toxicity of the reagents and by-products,<sup>74</sup> and the mildness of these reaction conditions have attracted much attention for improvement. Consequently, several research groups have devoted their focus towards investigating the use of sophisticated ligands, solvents, bases and recently the use of polymer-bound palladium catalysts with the aim of improving these procedures. Despite these significant advances, the Suzuki-Miyaura cross-coupling reaction has, since its discovery, exclusively been based on the utility of aryl boronic acid and their corresponding oxygenated esters as the coupling partners (**Scheme 78**).

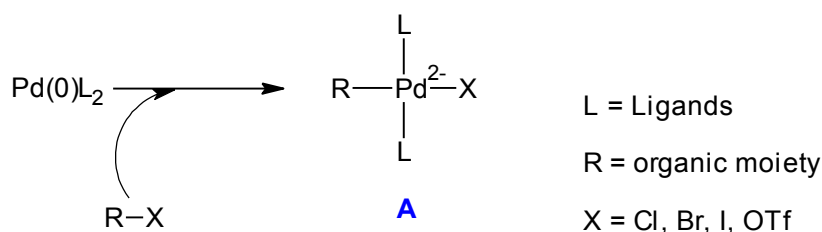


**Scheme 78**

To date, only few researchers have described the formation of carbon(aryl)–carbon(aryl) bonds with the use of other organoboron compounds as the nucleophilic coupling partners. It has only been recently that researchers have realised the desire to investigate other potential nucleophilic coupling partners in order to expand their scope thereby improving and generalizing this transformation.<sup>75</sup> Potassium heteroaryltrifluoroborate compounds have recently been demonstrated to be superior coupling partners that are advantageous compared to aryl boronic acids and their esters.<sup>76-78</sup>

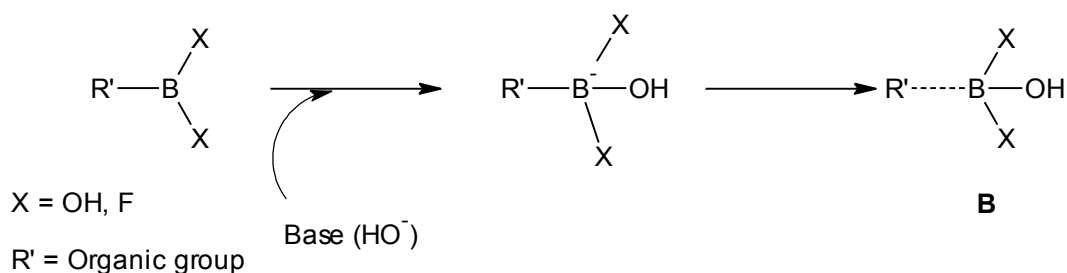
#### 4.5.2.1 Mechanism of the Suzuki-Miyaura Cross-Coupling Reaction.

The mechanism for the palladium-catalysed Suzuki cross-coupling reaction was first reported by Suzuki and Miyaura in 1985.<sup>79</sup> The mechanism was reported to involve the oxidation addition–transmetalation and reductive elimination sequences. The oxidation step has been set forward as the initial step of the mechanism, and has been shown to involve the addition of the organic halide to the zero-valent palladium centre to afford adduct **A** (Scheme 79).<sup>80, 81</sup>



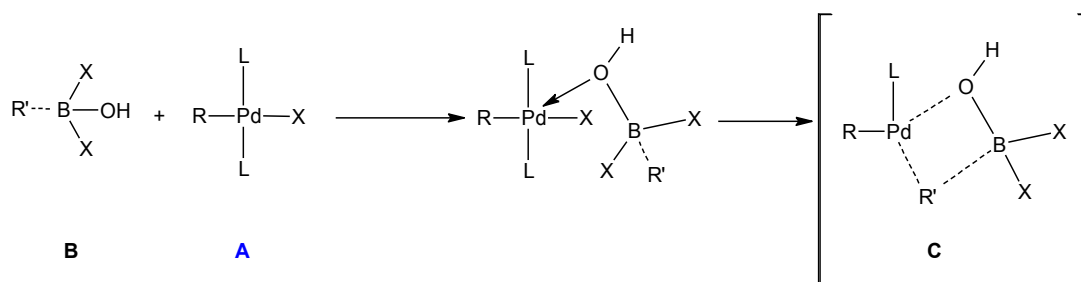
**Scheme 79**

During the transmetalation step, the organic moiety directly attached to the boron atom is transferred to the metal centre; however, extensive mechanistic studies have revealed that the transmetalation step greatly depends on the electron density of the participating organoboron compound.<sup>82</sup> The Soderquist group have reported that organoboron compounds that are more Lewis acidic (electron poor) undergo rapid complexation with the base which in turn increases the charge density on the boron atom (Scheme 6.4). This process has been reported to weaken the boron–carbon bond thus increasing the nucleophilicity of the attached organic group providing the organoboron complex **B** (Scheme 80).<sup>82, 83</sup>



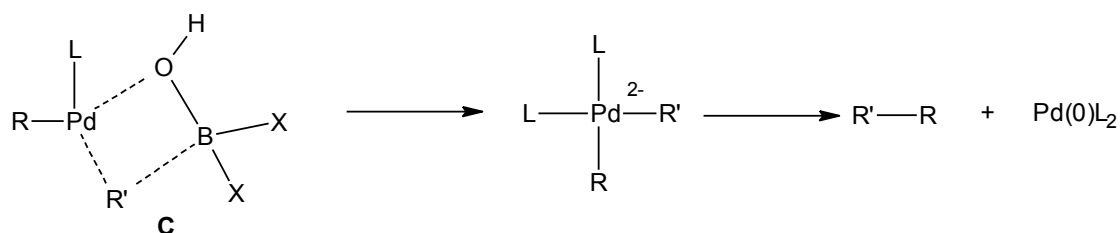
**Scheme 80**

The coordination of the palladium complex **A** with the organoboron complex **B** proceed through a four-centred transition state to afford complex **C** (**Scheme 101**).<sup>82</sup>



**Scheme 81**

During the reductive elimination step, the palladium complex **C** rearranges to locate the two organic moieties *cis* to each other. This step is followed by the elimination of the coupled-product from the metal centre which is accompanied by the reduction of the palladium from Pd(II) to Pd(0) (**Scheme 82**).



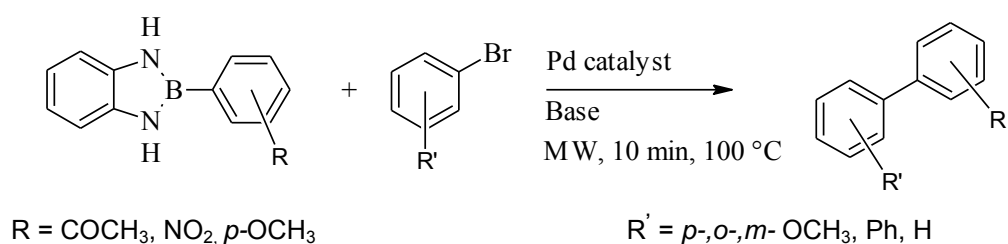
**Scheme 82**

According to the mechanism, it is apparent that the Lewis acidity of the organoboron compounds plays a crucial role in facilitating the transmetalation step. The greater the Lewis acidity of the organoboron compound the faster is the complexation with the base. The latter process is thought to increase the electron density donated to the vacant  $2p_z$ -orbital which in turn weakens the C–B bond thus accelerating the transmetalation step.<sup>82</sup>

In separate studies, Denk *et al.*<sup>84b</sup> and Hadebe<sup>84a</sup> independently reported that nitrogen-based organoborane compounds are electron rich when compared to their oxygenated-counterparts, as evidenced by higher degree of  $\pi$ -electrons back donated from the two chelating nitrogen atoms to the vacant  $2p_z$ -orbital of the boron atom. This observation was further supported by our UV-visible and fluorescence studies (Chapter 3) which showed that the vacant  $2p_z$ -orbital of the boron atom is indeed responsible for the extended  $\pi$ -communication between benzodiazaborolyl group and the attached organic  $\pi$ -system, indicating the electron density being donated to the vacant  $2p_z$ -orbital.<sup>85</sup>

Based on these rationalisations, we believe that the high electron density back donates from the two chelating nitrogen atom to the vacant  $2p_z$ -orbital would exert a considerable positive effect towards their reactivity during the transmetalation step. Because their enhanced charge density on the boron atom, these compounds are expected to undergo the transmetalation step with ease furnishing the desired coupled-products in excellent yields in shorter reaction times.

To the best of our knowledge, there are only few researchers who have directed their research focus towards improving the Suzuki cross-coupling reaction by investigating the utility of other organoborane compounds (other than arylboronic acid and their esters). Particularly, the application of nitrogen-based organoborane compounds (2-arylbenzo-1,3,2-diazaborole) have never been described as potential nucleophilic coupling partner in the Suzuki realm. This prompted us to investigate the Suzuki-Miyaura cross-coupling reaction of 2-arylbenzo-1,3,2-diazaborole compounds with aryl halides bearing electron-withdrawing or electron-donating functional groups (**Scheme 83**).



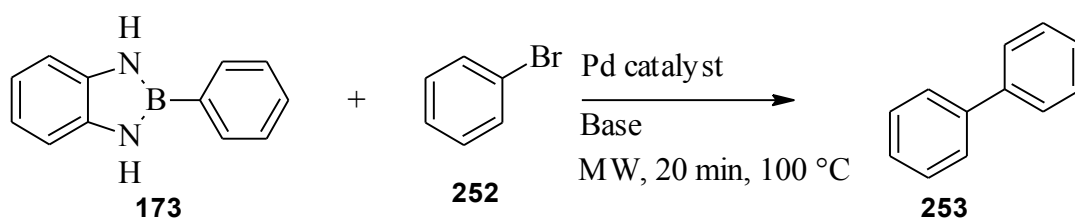
**Scheme 83**



Initially, an optimisation study was conducted on the cross-coupling reaction between the corresponding aryl bromides and the benzodiazaborolyl derivatives. In this study, 2-phenylbenzo-1,3,2-diazaborole was reacted with bromobenzene as an electrophilic coupling partner (Table 4.1). This reaction was repeated several times varying palladium catalysts (Table 4.1).

Encouraged by the effect of the microwave irradiation in our previous study (Chapter two), we thought that it would be logical to conduct these reactions under the influence of the microwave energy.<sup>86</sup>

**Table 4.1:** Optimisation study between 2-phenylbenzo-1,3,2-diazaborole **173** with bromobenzene, an optimal reaction conditions survey.



Entry	Pd Cat.	Ligand	Base	Yields (%) <sup>b</sup> <b>5</b>
1	PdCl <sub>2</sub>	None	none	0
2	PdCl <sub>2</sub>	PPh <sub>3</sub>	K <sub>3</sub> PO <sub>4</sub>	< 5
3	Pd (PPh <sub>3</sub> ) <sub>4</sub>	None	K <sub>2</sub> CO <sub>3</sub>	21
4	Pd (PPh <sub>3</sub> ) <sub>2</sub>	None	K <sub>2</sub> CO <sub>3</sub>	18
5	Pd (PPh <sub>3</sub> ) <sub>4</sub>	None	K <sub>3</sub> PO <sub>4</sub> ·H <sub>2</sub> O	10
6	Pd (PPh <sub>3</sub> ) <sub>2</sub>	PCy <sub>3</sub>	K <sub>3</sub> PO <sub>4</sub> ·H <sub>2</sub> O	33
7	PdCl <sub>2</sub>	PCy <sub>3</sub>	K <sub>3</sub> PO <sub>4</sub> ·H <sub>2</sub> O	< 5
8	Pd(OAc) <sub>2</sub>	PPh <sub>3</sub>	K <sub>2</sub> CO <sub>3</sub>	51
9	Pd(OAc) <sub>2</sub>	PCy <sub>3</sub>	K <sub>3</sub> PO <sub>4</sub> ·H <sub>2</sub> O	88
10	Pd(OAc) <sub>2</sub>	PCy <sub>3</sub> / PPh <sub>3</sub> <sup>c</sup>	K <sub>3</sub> PO <sub>4</sub>	67
11	Pd(OAc) <sub>2</sub>	PCy <sub>3</sub>	K <sub>2</sub> CO <sub>3</sub>	76
12	Pd (PPh <sub>3</sub> ) <sub>2</sub>	PPh <sub>3</sub>	K <sub>2</sub> CO <sub>3</sub>	20

<sup>a</sup> Reaction conditions : compound **173** (0. 77 mmol), bromobenzene (0.50 ml), Pd cat. (4 mol %), ligand (8 mol %), base (3 equiv.) and water (0.1 ml). Closed vessel, 80 Watts of microwave energy, 100 °C, 100 Psi of pressure, 10 minutes. <sup>b</sup> Isolated yields after column chromatography. <sup>c</sup> 4 mol% each of the ligands.

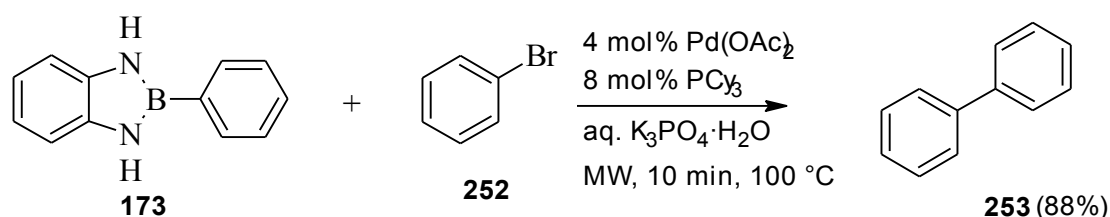
Attempted cross-coupling reaction of compound **173** with bromobenzene in the absence of both the ligand and base gave zero conversion of the starting materials (Table 1, entry 1). These results clearly suggested that the base and ligand are crucial

for the cross-coupling reaction in hand.<sup>17</sup> The addition of PPh<sub>3</sub> ligand and K<sub>3</sub>PO<sub>4</sub> base failed to afford any of the desired coupled-product in quantitative yields (Table 1, entry 2). Poor conversion of both starting material was also noted with the use of a bulky Pd(PPh<sub>3</sub>)<sub>4</sub> catalyst (Table 1, entries, 3 and 5). The use of Pd(PPh<sub>3</sub>)<sub>2</sub> catalyst in conjunction with PPh<sub>3</sub> ligand and K<sub>2</sub>CO<sub>3</sub> or K<sub>3</sub>PO<sub>4</sub>·H<sub>2</sub>O also failed to optimise the reaction conditions (Table 1, entries 4, 6 and 12). This observation was attributed to the decomposition of Pd(PPh<sub>3</sub>)<sub>2</sub> catalyst to Pd-black. Moderate to good yields (67%-88%) were obtained with the use of Pd(OAc)<sub>2</sub> and PCy<sub>3</sub> or the combination of PCy<sub>3</sub> and PPh<sub>3</sub> as supporting ligands (Table 1, entries 9-11). With the optimized reaction condition in hand {(Pd(OAc)<sub>2</sub> as catalyst, PCy<sub>3</sub> as supporting ligand, K<sub>3</sub>PO<sub>4</sub>·H<sub>2</sub>O as base and water}, several aryl bromides bearing either the electron-withdrawing or electron-donating substituents were reacted with 2-arylbenzo-1,3,2-diazaborolane compounds under the optimised reaction conditions.

The synthesis of asymmetrical biaryls under the optimal reaction conditions were conducted following two different approaches (A and B) depending on the physical state of the substrate. Liquid aryl bromides were coupled to 1,3,2-diazaborolane following general procedure A and the solid substrates were coupled *via* general procedure B.

#### 4.5.2.2 Representative Procedure for Solvent free Reactions (A)

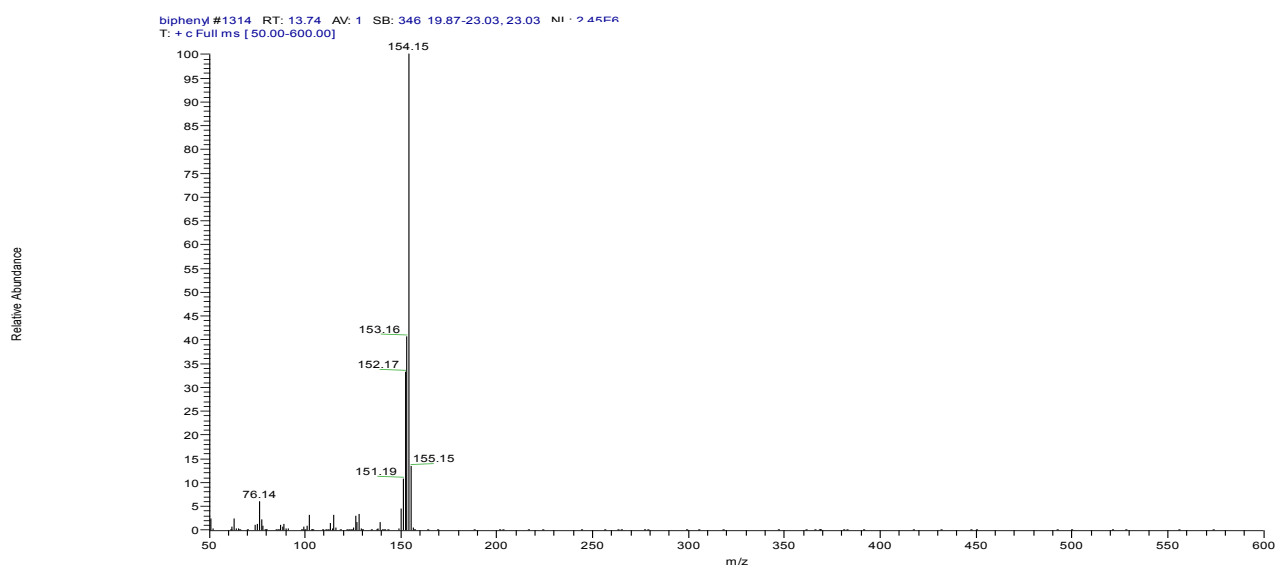
##### 4.5.2.2.1 Synthesis of Biphenyl (253)



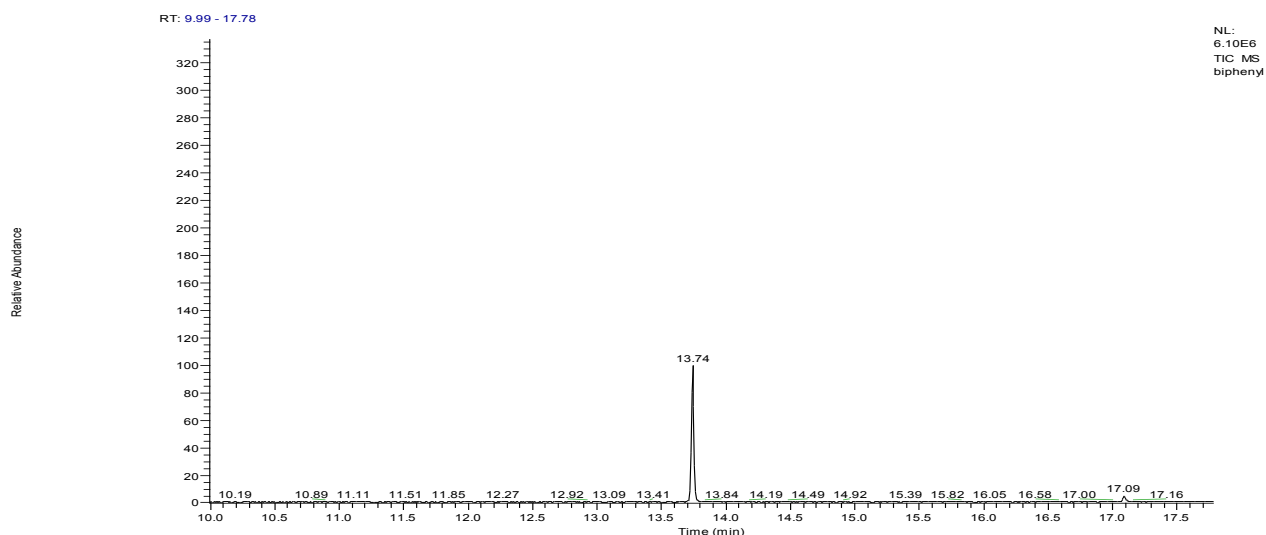
**Scheme 84**

Biphenyl (**253**) was prepared in an isolated yield of 88% as a cream white solid from the reaction of 2-phenylbenzo-1,3,2-diazaborolane (**173**) and bromobenzene (**252**). The yield of the coupled product (**253**) obtained is comparable to the yield of 88% obtained by Chandrasekhar and co-workers<sup>87</sup> after refluxing the reaction mixture for more than 5 hours (**Scheme 84**). The structure and the purity of the product were

confirmed using spectroscopic techniques ( $^1\text{H}$ ,  $^{13}\text{C}$  NMR and GC-MS). The  $^1\text{H}$  NMR spectrum of the obtained cream white solid was consistent with the expected structure as evident with the integral ratios corresponding to the desired product (**253**). The purity of the product was also confirmed by GC-MS which showed one major peak with a retention time of 13.7 minutes corresponding to a molecular ion peak  $[\text{M}^+]$  with a molecular mass of  $154\text{ g.mol}^{-1}$  (**Figures 50 and 51**). The melting point of the desired product was found to be in the range of  $69\text{-}70\text{ }^\circ\text{C}$  which is similar to that reported by Zhang *et al.* of  $69\text{-}70\text{ }^\circ\text{C}$ .<sup>88</sup>



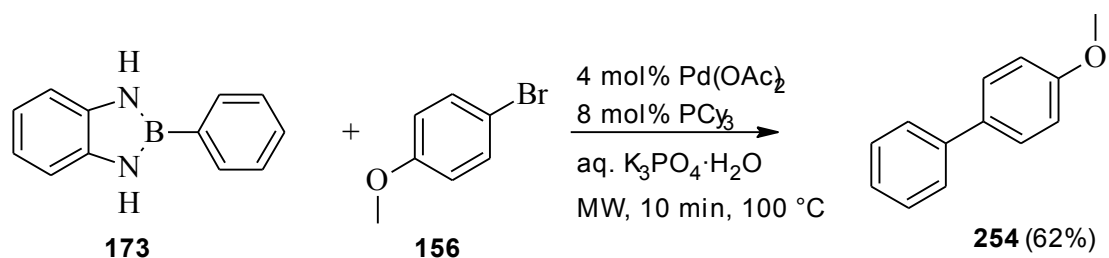
**Figure 50: GC spectrum for compound 253**



**Figure 51: GC trace for compound 253**

#### 4.5.2.2.2 Synthesis of 4-phenylanisole (254)

The preparation of 4-phenylanisole (**254**) was successfully achieved by the reaction of 2-phenylbenzo-1,3,2-diazaborolane (**173**) and 4-bromoanisole (**156**) following the general procedure A (**Scheme 85**). 4-Phenylanisole (**254**) was synthesised in 62%, a yield which is significantly higher than the yield reported by Bezier and co-workers (35%).<sup>89</sup>



**Scheme 85**

The <sup>1</sup>H NMR spectrum of the desired-product showed the integral ratios corresponding to the expected number of protons and the assignments are depicted in **Figure 53**. According to the COSY spectrum, the protons whose singlet resonates at δ 3.87 ppm was not coupled to any of the other protons and was assigned to the methoxy group. The doublet protons (with *J* = 8.9 Hz) are coupled to protons whose multiplet appears in the range δ 7.56-7.60 ppm. The former protons are assigned to 2-H and 6-H, and the latter to protons 2'-H, 6'-H, 5-H and 6-H. The triplet resonating at δ 7.43 ppm (*J* = 7.3 Hz) is coupled to a multiplet resonating in the range δ 7.32-7.38 ppm, these protons were assigned to protons 3'-H, 5'-H and 4'-H. The <sup>13</sup>C NMR spectrum of the desired product was similar to that obtained by Bezier and co-worker.<sup>89</sup> The title compound was obtained as a white solid which melts in the range of 92-93 °C which is in good agreement with the literature melting point of 90-91 °C.<sup>90</sup> The GC trace of the desired product showed a single peak with a retention time of 17.2 minutes corresponding to the expected molecular mass for C<sub>13</sub>H<sub>12</sub>O of 184. The infrared analysis showed a strong sharp band resonating at 1240 cm<sup>-1</sup> which corresponds to the O—CH<sub>3</sub> bond stretching frequency.

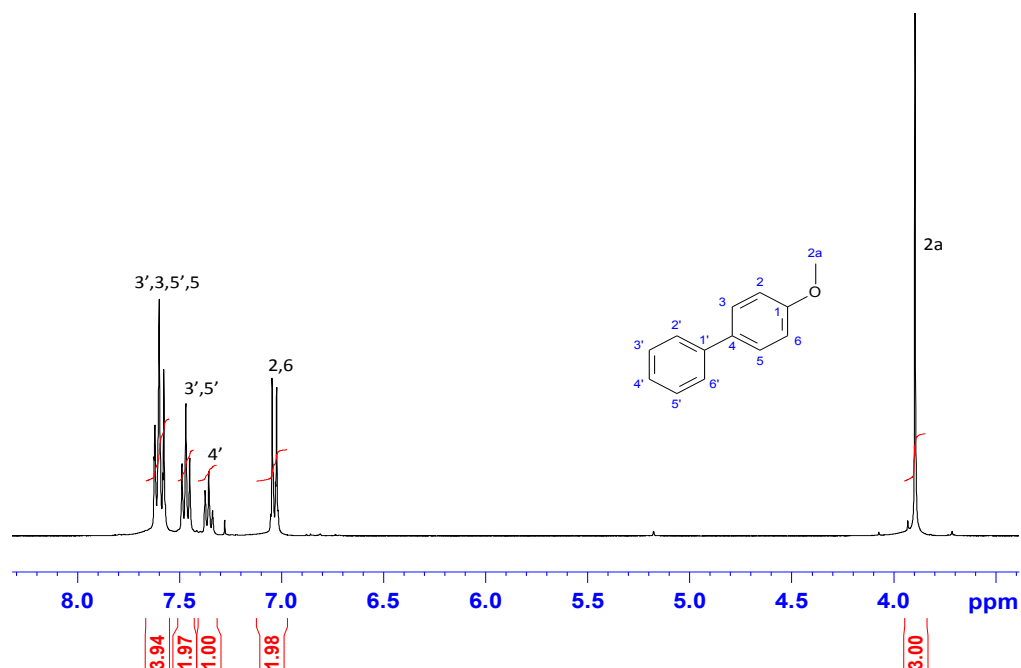
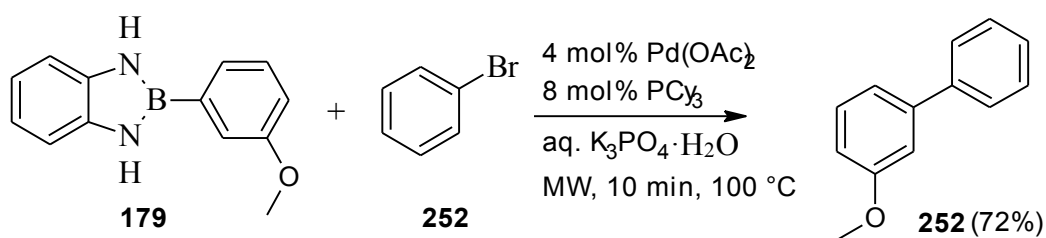


Figure 53:  $^1\text{H}$  NMR spectrum for compound 254.

#### 4.5.2.2.3 Synthesis of 3-phenylanisole (255)

With 2-(3-methoxyphenyl)-benzo-1,3,2-diazaborolane (**179**) in hand, 3-phenylanisole (**255**) could be successfully synthesised from the cross-coupling reaction of 2-(3-methoxyphenyl)-benzo-1,3,2-diazaborolane (**179**) with bromobenzene (**252**) as a clear oil in 72% isolated yield (**Scheme 86**).

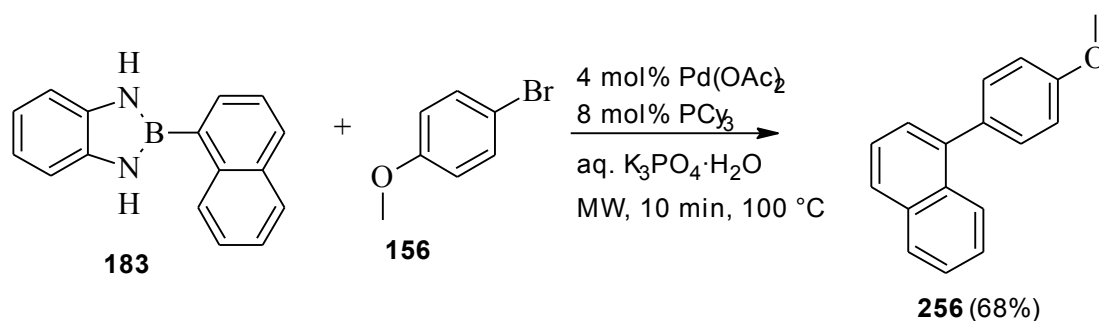


Scheme 86

The structure and the purity of the product were confirmed with spectroscopic data ( $^1\text{H}$ ,  $^{13}\text{C}$  NMR and GC-MS). The  $^1\text{H}$  NMR spectrum confirmed the existence of the product and revealed it to be clean as evident by the integral ratios corresponding to the expected number of protons expected in the desired product (**255**). The purity of the product was also confirmed with GC-MS which showed one major peak with a retention time of 16.9 minutes corresponding to the calculated molecular mass for  $\text{C}_{13}\text{H}_{12}\text{O}$  of 184.<sup>91</sup>

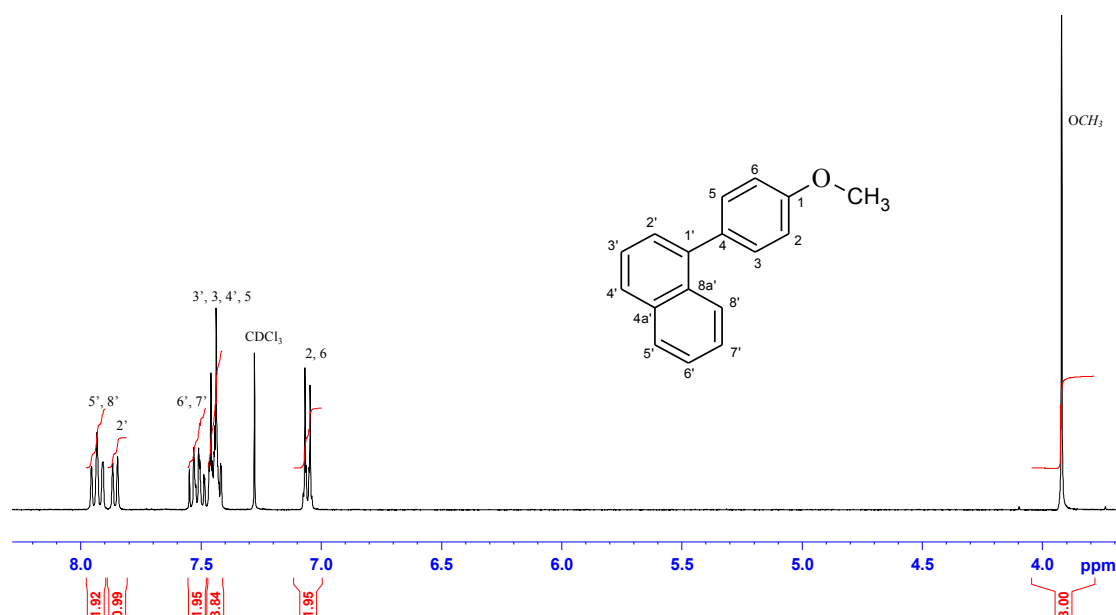
#### 4.5.2.2.4 Synthesis of 1-(4-methoxyphenyl)-naphthalene (256)

1-(4-Methoxyphenyl)-naphthalene (**256**) was synthesised in 68% isolated yield from the reaction of 2-(1-naphthalenyl)-benzo-1,3,2-diazaborolane (**183**) with 4-bromoanisole (**156**) (**Scheme 87**). The yield obtained compares favourably with the yield of 72% achieved by Quasdorf and co-workers after 24 hours of reflux.<sup>92</sup>



**Scheme 87**

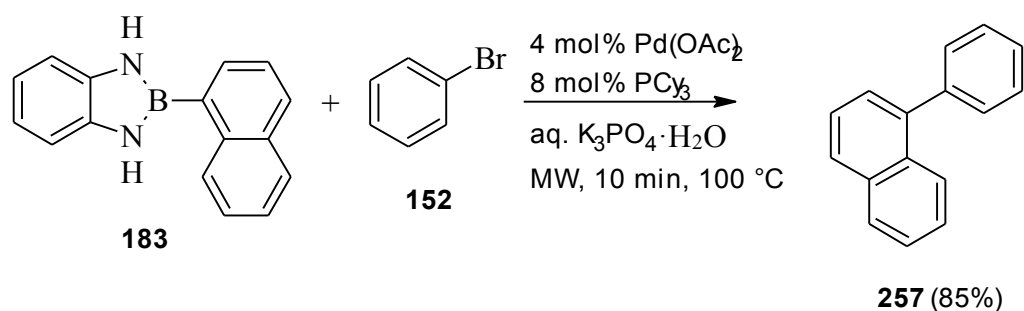
The  $^1\text{H}$  and  $^{13}\text{C}$  NMR spectroscopic data of the obtained product are consistent with the anticipated structure and assignments are depicted in Figure 66 below. The title compound was obtained as white crystals which melts in the range of 116-117  $^\circ\text{C}$  and agrees favourably with the literature melting point of 116-117  $^\circ\text{C}$ .<sup>93</sup> A strong band at 1239  $\text{cm}^{-1}$  in the infrared spectrum of the desired-product confirmed the presence of a methoxy group, as it corresponds to  $\text{O}-\text{CH}_3$  stretching vibration.



**Figure 54:**  $^1\text{H}$  NMR spectra for compound **256**.

#### 4.5.2.2.5 Synthesis of 1-(phenyl)-naphthalene (257)

Bromobenzene (**252**) was reacted with 2-(1-naphthalenyl)-benzo-1,3,2-diazaborolane (**183**) to afford the title compound in a yield of 85% after isolation (**Scheme 88**). This yield is significantly higher than the 66% yield obtained by Chandrasekhar and co-workers<sup>94</sup> from the reaction of the corresponding boronic acid as a coupling partner.

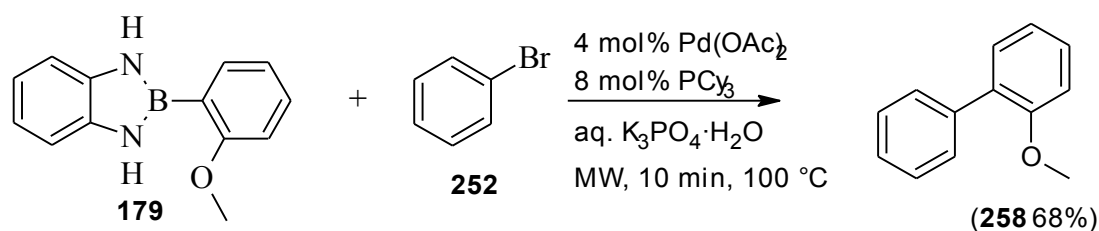


**Scheme 88**

The <sup>1</sup>H and <sup>13</sup>C NMR spectra of the desired product are in good agreement with that reported in literature. The product was obtained as clear oil, which is consistent with the finding of Qin and co-worker.<sup>95</sup>

#### 4.5.2.2.6 Synthesis of 2-phenylanisole (258)

The synthesis of 2-phenylanisole (**258**) from 2-(2-methoxyphenyl)benzo-1,3,2-diazaborolane (**179**) as a coupling partner has proven more efficient than its synthesis from the corresponding boronic acid (**Scheme 89**).

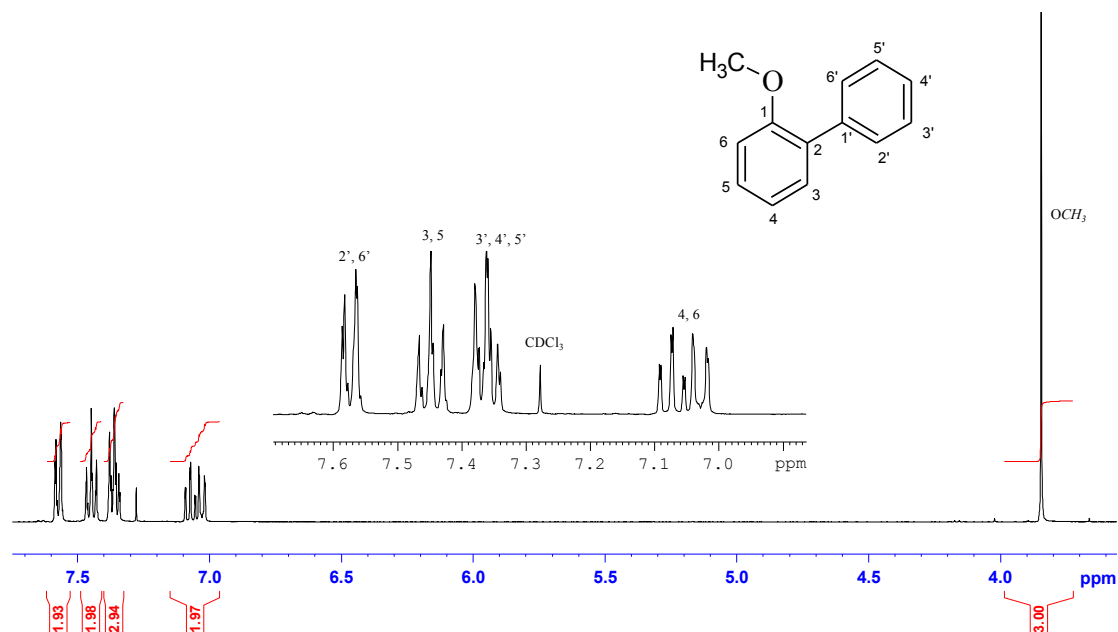


**Scheme 89**

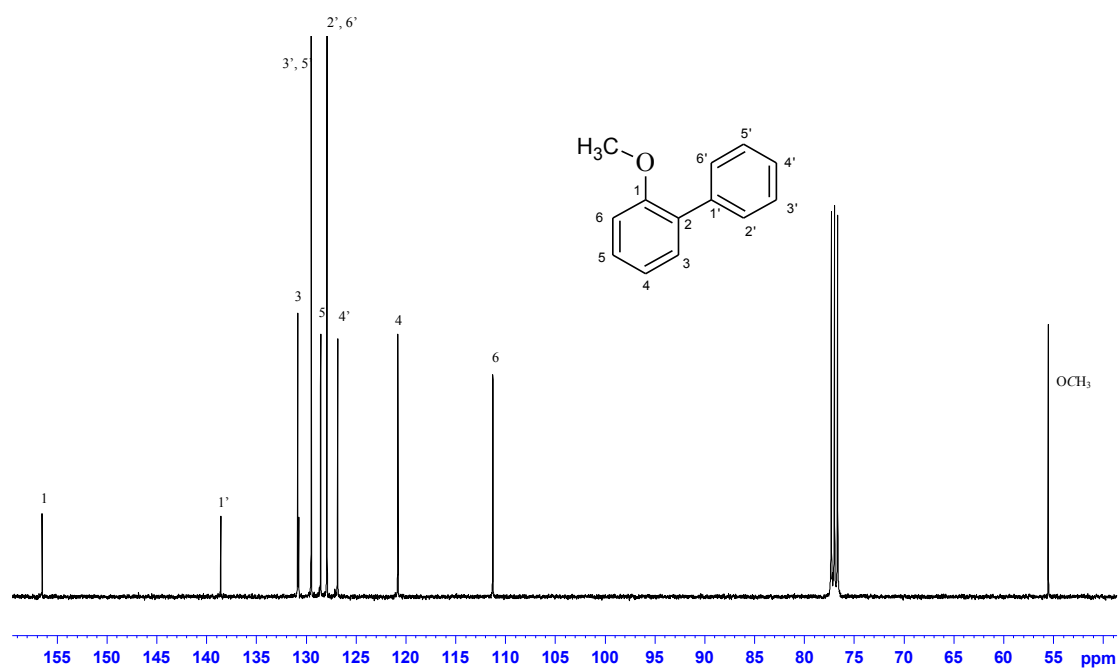
2-Phenylanisole (**258**) was obtained in a yield of 68% which is higher than the 40% yield obtained when the corresponding boronic acid was used.<sup>96</sup> 2-Phenylanisole was obtained as a clear oil and this observation was supported by the findings of Wei and co-workers.<sup>97</sup> The GC-MS spectrum showed a peak with a relative abundance of 100%, this peak resonates at 184 which correspond to the molecular ion of the desired product.



The structure and the purity of the title compound was confirmed using  $^1\text{H}$  and  $^{13}\text{C}$  NMR spectroscopic data, and the assignments are depicted in **Figures 55** and **56** below.



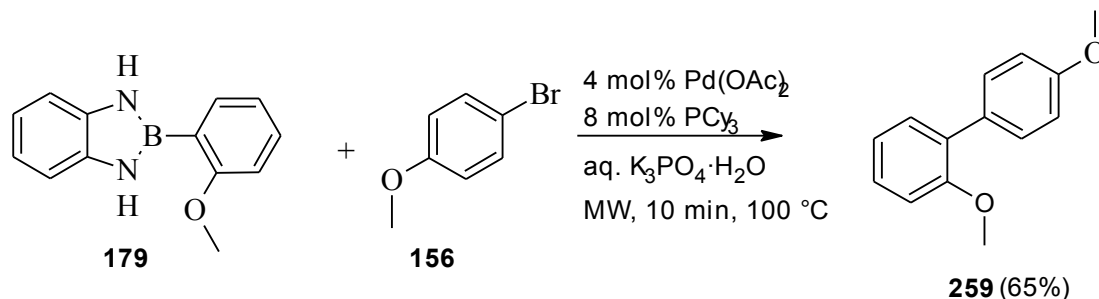
**Figure 55:  $^1\text{H}$  NMR spectrum for compound 258**



**Figure 56:  $^{13}\text{C}$  NMR spectrum for compound 258**

#### 4.5.2.2.7 Synthesis of 4-(2-methoxyphenyl)-anisole (259)

The title compound was synthesised in 65% from the cross coupling reaction between 2-(2-methoxyphenyl)-benzo-1,3,2-diazaborole (**179**) with 4-bromoanisole (**156**). The yield obtained from this coupling reaction is lower than the 98% yield (**Scheme 90**).

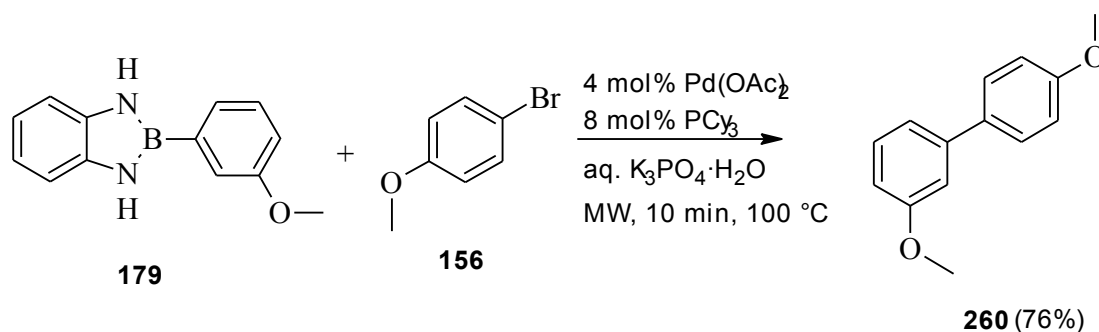


**Scheme 90**

The low yield obtained from this reaction was attributed to poor reactivity of **179** as evident by a large amount of this starting material recovered after the reaction as well as the formation of undesired products. These observations are supported by Marcuccio and co-workers<sup>98</sup> who also reported that organoborane compounds bearing electron-donating substituents are susceptible to homocoupling with the phosphine ligands, resulting in the formation of undesirable products.<sup>98</sup> Attempts to increase the reaction time to 20 minutes did not provide any improvements in overall yields of the reaction. The structure and the purity of the product were confirmed using <sup>1</sup>H and <sup>13</sup>C NMR spectra which proved to be consistent with the literature reports. The melting point of the desired product was recorded in the range of 69-70 °C which agrees favourably to the reported melting range of 69-70 °C.<sup>99</sup>

#### 4.5.2.2.8 Synthesis of 4-(3-methoxyphenyl)-anisole (260)

4-(3-Methoxyphenyl)-anisole (**260**) was furnished in 76% yield, after purification, when 2-(3-methoxyphenyl)-benzo-1,3,2-diazaborolane (**179**) was coupled to 4-bromoanisole (**156**) (**Scheme 91**).



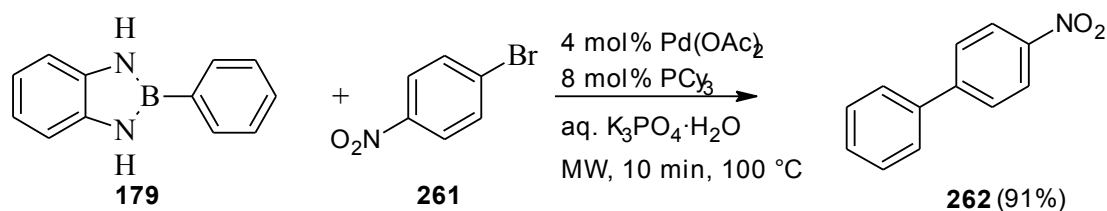
## Scheme 91

The  $^1\text{H}$  and  $^{13}\text{C}$  NMR spectra are in good agreement with the expected structure and the GC trace confirmed the purity of the product as evidenced with a single major peak with a retention time of 16.9 minutes corresponding to the expected molar mass of 184. The melting point temperature was observed in the range of 56-57 °C which is consistent with the literature range of 58-59 °C reported by Itoh *et al.*<sup>100</sup>

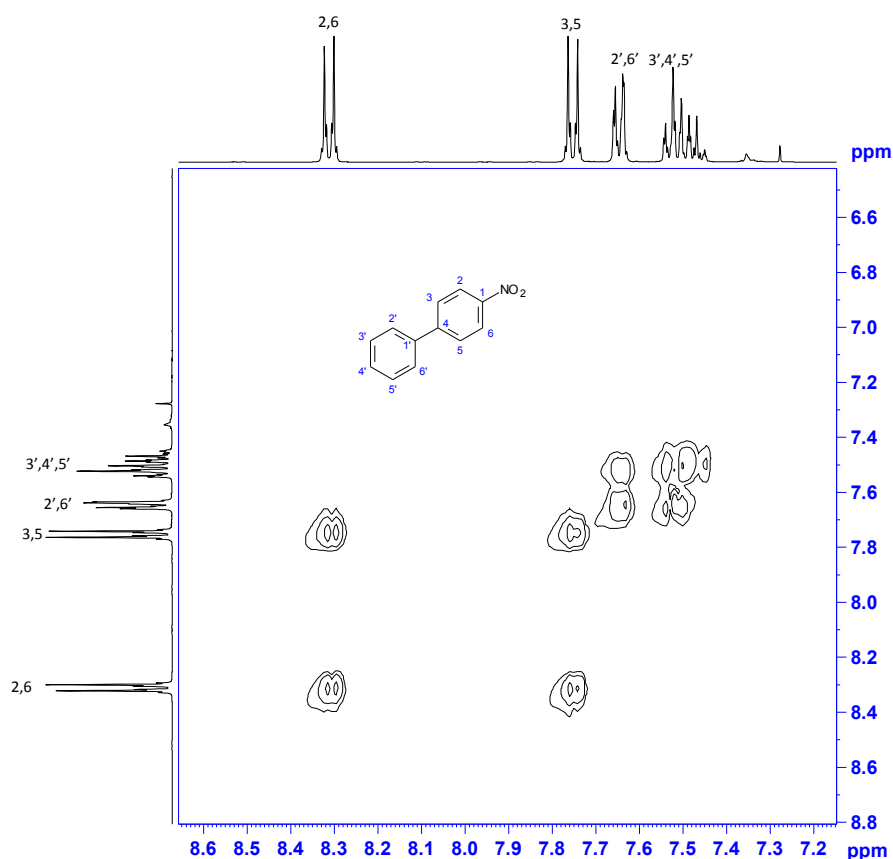
### 4.5.2.3 Representative Procedure for Solid Substrates

#### 4.5.2.3.1 Synthesis of 4-phenylnitrobenzene (262)

4-Phenylnitrobenzene (**262**) was successfully synthesised from the reaction of 4-bromonitrobenzene (**261**) with 2-phenylbenzo-1,3,2-diazaborolane (**176**) (**Scheme 112**). The product was obtained in an isolated yield of 91% which is higher than 86% yield obtained from the corresponding boronic acid as coupling partner reported by Schweizer *et al.*<sup>101</sup> The melting point of the product was recorded in the range of 112-114 °C and compares well with the literature value of 112-114°C.<sup>102</sup>



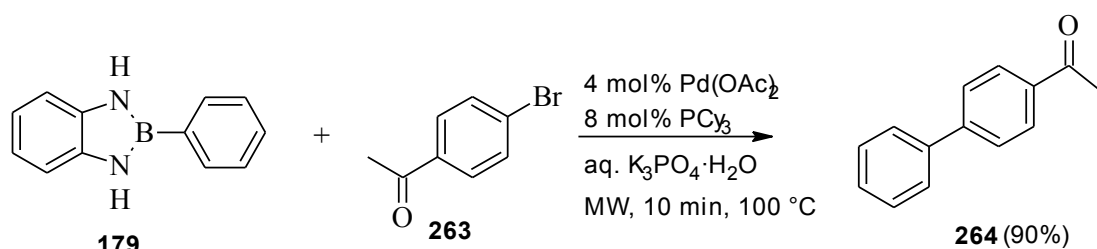
Scheme 92



**Figure 57: COSY NMR spectrum for compound 262**

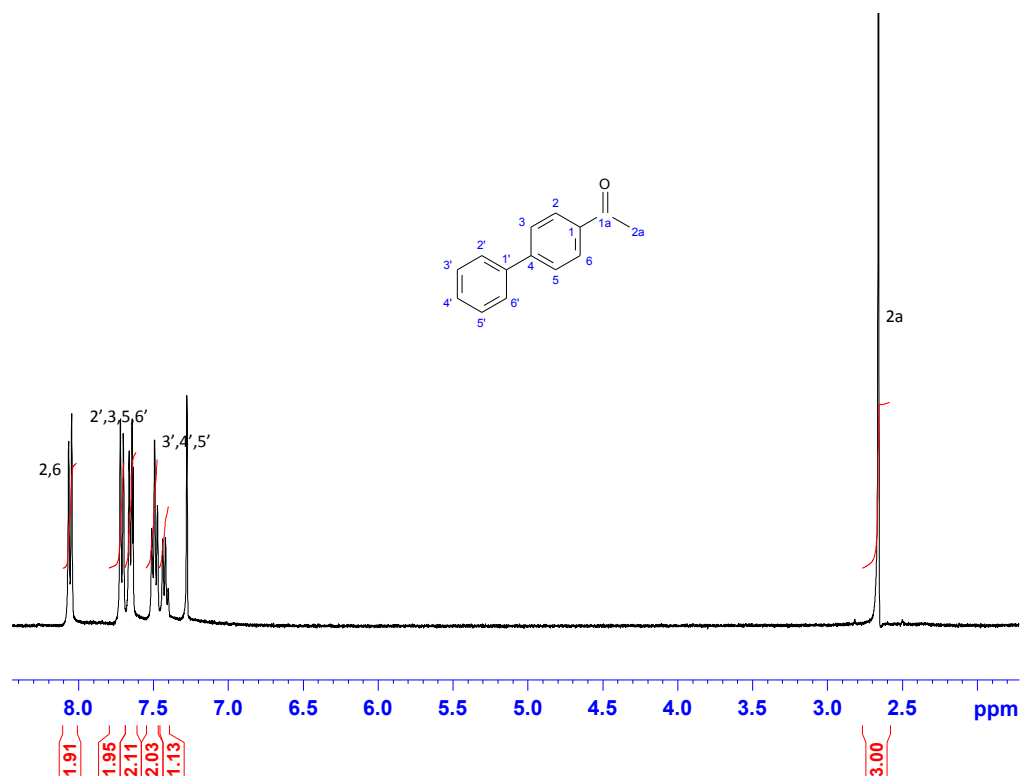
#### 4.5.2.3.2 Synthesis of 4-phenylacetophenone (264)

The cross-coupling reaction of 2-phenylbenzo-1,3,2-diazaborolane (**179**) with 4-bromoacetophenone (**263**) afforded 4-phenylacetophenone (**264**) in 90% isolated yield in 10 minutes (**113**). The yield of the coupled product (**264**) obtained is higher than 85% yield achieved by Chandrasekhar and co-workers<sup>94</sup> using boronic acid as the coupling partner after heating the mixture under reflux for 10 hours.



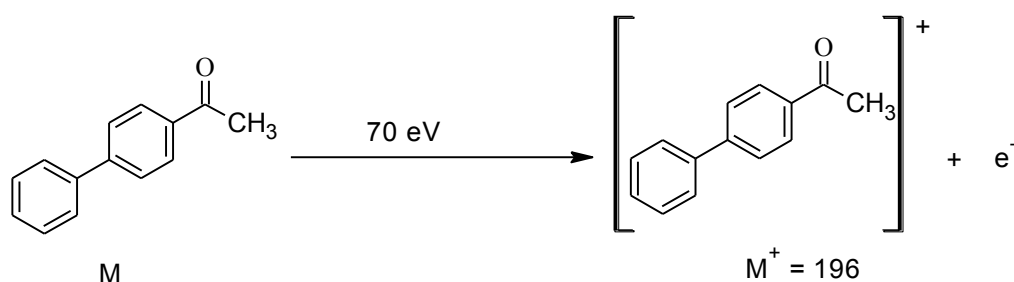
**Scheme 93**

To confirm the structure of the product, the <sup>1</sup>H NMR spectrum of the product was acquired and it revealed the expected peaks with the integral ratios exactly matching the number of protons (**Figure 58**).



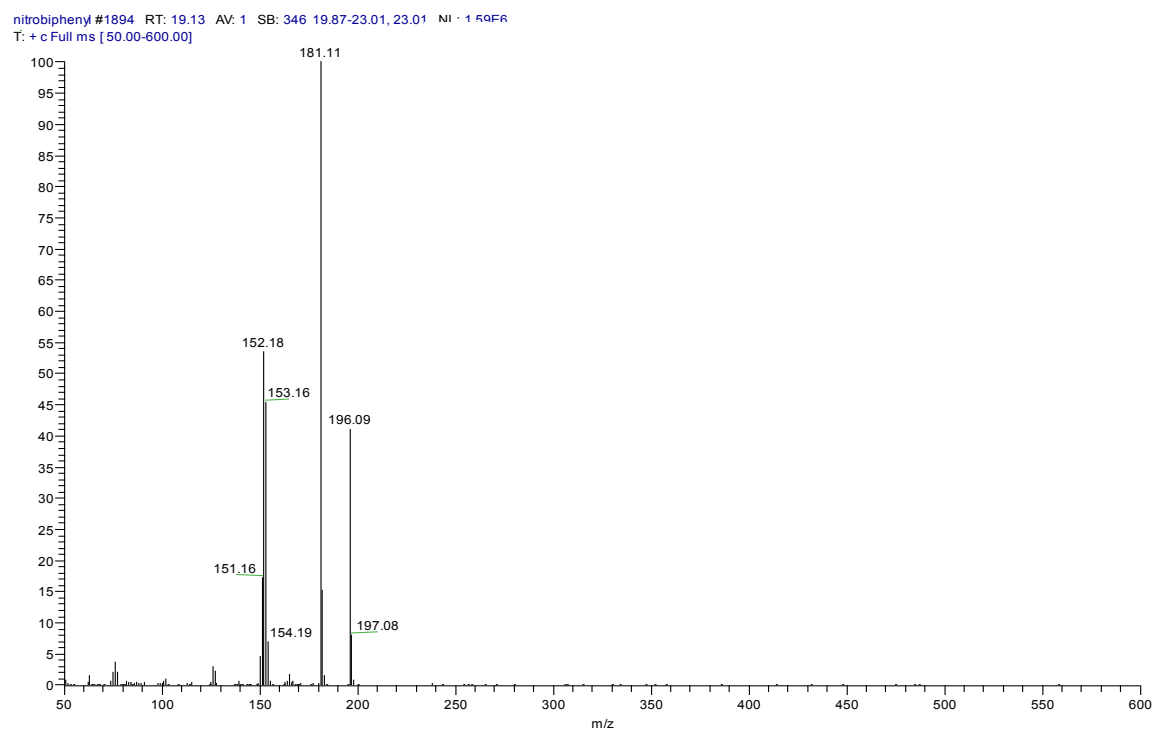
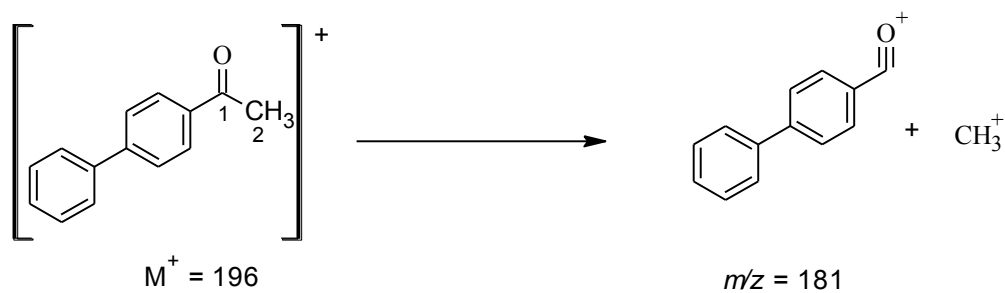
**Figure 58:**  $^1\text{H}$  NMR spectra for compound **264**

GC-MS (**Figure 59**) showed a molecular ion peak  $[\text{M}^+]$  with an  $m/z$  value of 196  $\text{g. mol}^{-1}$  which results when **264** is bombarded with a beam of high-energy electron such that it loses an electron and becomes positively charged (**Scheme 94**)



**Scheme 94**

The base peak with an  $m/z$  value of 181 mass units is due to a  $\text{C}_1\text{--C}_2$  fragmentation. The cleavage of this bond leads to the formation of stable fragment ions ( $\text{C}_{13}\text{H}_9\text{O}^+$ ) and  $\text{CH}_3^+$  with the former ion having a relative abundance of 100% (**Scheme 95**).



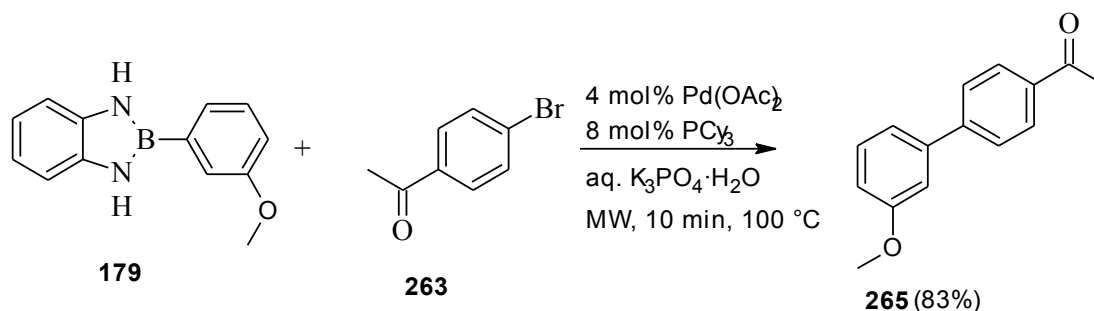
**Figure 59: GC spectrum for compound 246**

The infrared spectrum of the product confirmed the presence of the carbonyl functionality as evident with a broad absorption band at  $1675\text{ cm}^{-1}$  corresponding to the stretching vibration of C=O bond. The melting point of the product was found to be in the range  $120\text{-}124\text{ }^{\circ}\text{C}$  which is consistent with the reported melting point of  $122\text{-}124\text{ }^{\circ}\text{C}$ .<sup>103</sup> The  $^{13}\text{C}$  NMR spectrum is also consistent with the anticipated structure as evident by ten carbons peaks as expected.

#### 4.5.2.3.3 Synthesis of 4-(3-methoxyphenyl)-acetophenone (265)

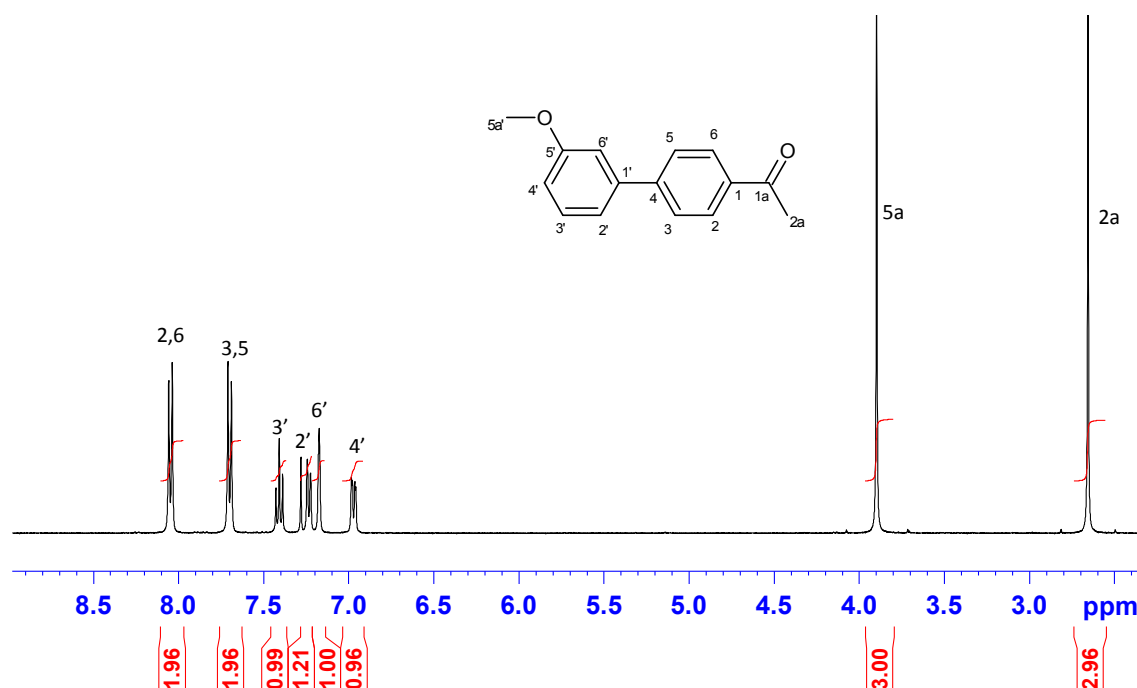
The cross coupling reaction of 2-(3-methoxyphenyl)-benzo-1,3,2-diazaborolane (**180**) with 4-bromoacetophenone (**263**) afforded 2-(3-methoxyphenyl)acetophenone (**265**) in 83% isolated yield (**Scheme 116**). Our yield is higher than the 36% and 77% yields

achieved by Saito *et al.*<sup>104</sup> when they used the corresponding boronic acid as coupling partner. The <sup>1</sup>H NMR spectrum of the product revealed the product to be clean and is consistent with the predicted spectrum (**Figure 59**).



**Scheme 96**

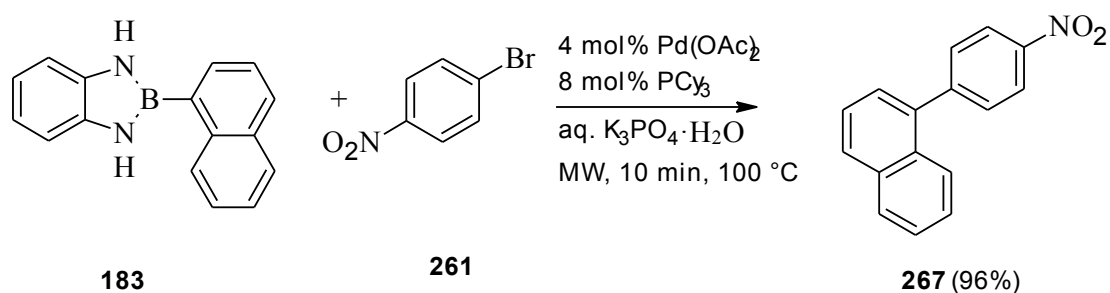
GC-MS trace of the product showed a peak with a retention time of 21.7 minutes, corresponding to calculated molecular mass for C<sub>15</sub>H<sub>14</sub>O<sub>2</sub> of 226. The infrared spectrum of the product confirmed the presence of a carbonyl functionality as evident by the characteristic absorption band at 1670 cm<sup>-1</sup> which corresponds to the C=O stretching vibration. The purity of the product was also confirmed by the melting point temperature, which was found to be in the range of 88-90 °C, and matches exactly the range reported in the literature.<sup>91</sup>



**Figure 60:** <sup>1</sup>H NMR spectrum for compound 265.

#### 4.5.2.3.4 Synthesis of 1-(4-nitrophenyl)-naphthalene (267)

1-(4-Nitrophenyl)-naphthalene (**267**) was prepared in 96% isolated yield as a cream white solid from the reaction of 2-(1-naphthalenyl)benzo-1,3,2-diazaborole (**185**) and 4-bromonitrobenzene (**261**) (**Scheme 97**). The 96% yield obtained compares favourably with 91% yield reported in literature after heating the reaction mixture for 1.5 hours.

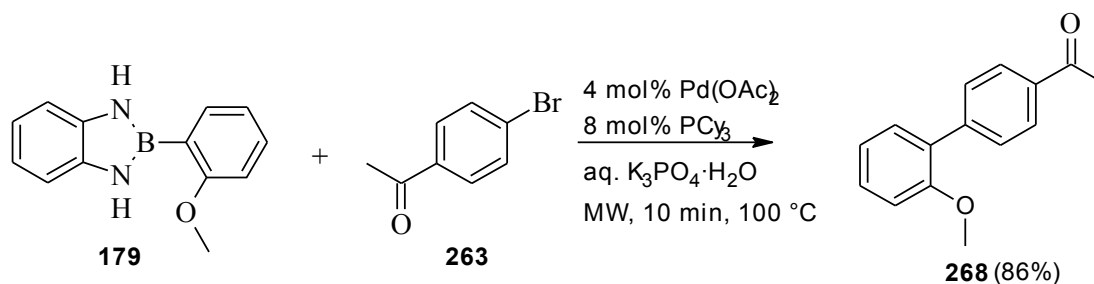


**Scheme 97**

The structure and the purity of the product were confirmed by spectroscopic data (<sup>1</sup>H, <sup>13</sup>C NMR and GC-MS). The <sup>1</sup>H NMR spectrum confirmed the existence of the product and revealed it to be relatively clean as evident by the integral ratios corresponding to the desired product (**268**). The GC-MS showed one major peak at a retention time of 20.2 minutes corresponding to the calculated mass for C<sub>16</sub>H<sub>14</sub>NO<sub>2</sub> of 249. The melting point of the title compound was found to be 132-133 °C which matches exactly the melting range reported by Qin and co-workers.<sup>95</sup>

#### 4.5.2.3.5 Synthesis of 4-(2-methoxyphenyl)-acetophenone (268)

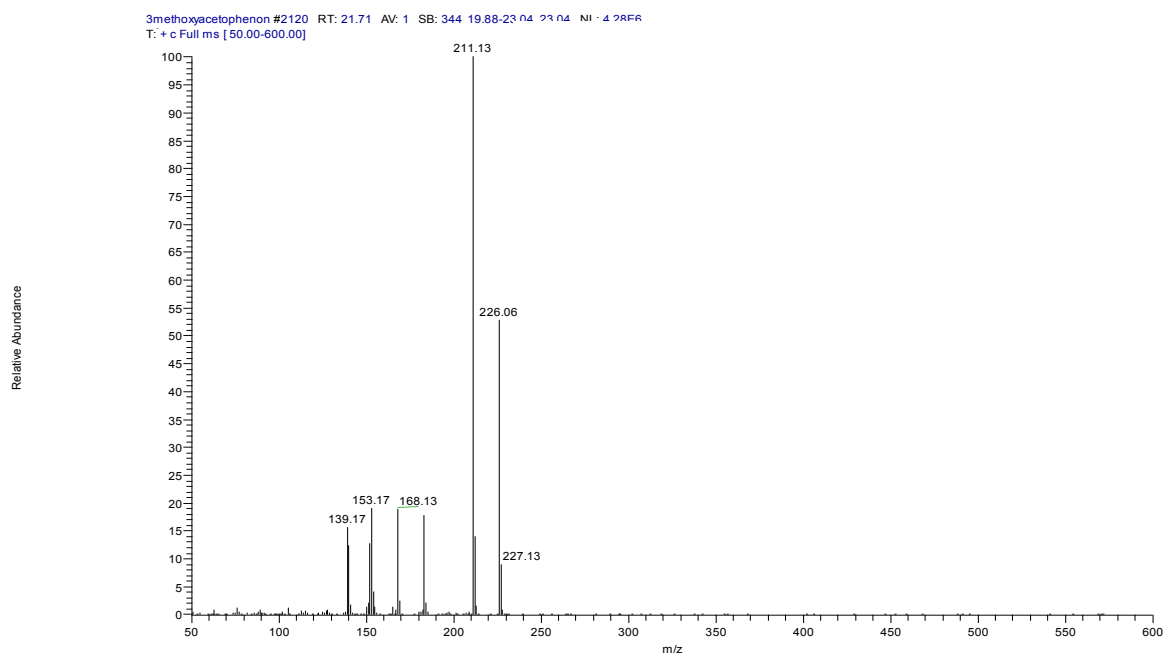
2-(2-Methoxyphenyl)-benzo-1,3,2-diazaborole (**179**) was coupled successfully with 4-bromoacetophenone (**263**) to afford 2-(methoxyphenyl)-acetophenone (**268**) in 86% isolated yield (**Scheme 98**).



**Scheme 98**



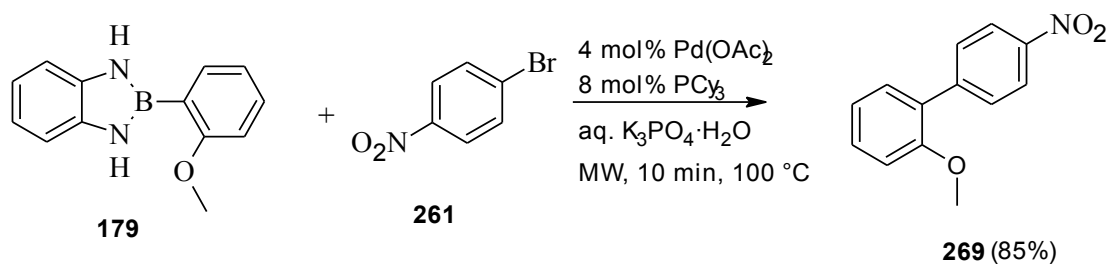
The  $^1\text{H}$  and  $^{13}\text{C}$  NMR spectra were used to assess the purity and confirm the structure of the product. Careful assignment of both the  $^1\text{H}$  and  $^{13}\text{C}$  NMR spectra revealed the expected product to be clean. The melting point temperature of the coupled product **268** was registered at 105-107°C which is in good agreement with the literature value of 105-106°C.<sup>105</sup> The GC-MS spectrum of the product showed a base peak with an  $m/z$  value of 211 mass units corresponding to the fragment ion ( $\text{C}_{14}\text{H}_{11}\text{O}_2^+$ ) (**Figure 61**). The peak with the relative abundance of *ca.* 55% corresponds to the molecular ion as it has an  $m/z$  value of 226 matching the calculated molar mass for  $\text{C}_{15}\text{H}_{12}\text{O}_2$  of 226. The infrared spectrum showed the presence of a sharp absorption bands at 1239  $\text{cm}^{-1}$  and 1670  $\text{cm}^{-1}$  corresponding to the stretching vibrations of the O—CH<sub>3</sub> and C=O bonds, respectively.



**Figure 61: GC spectrum for compound 268**

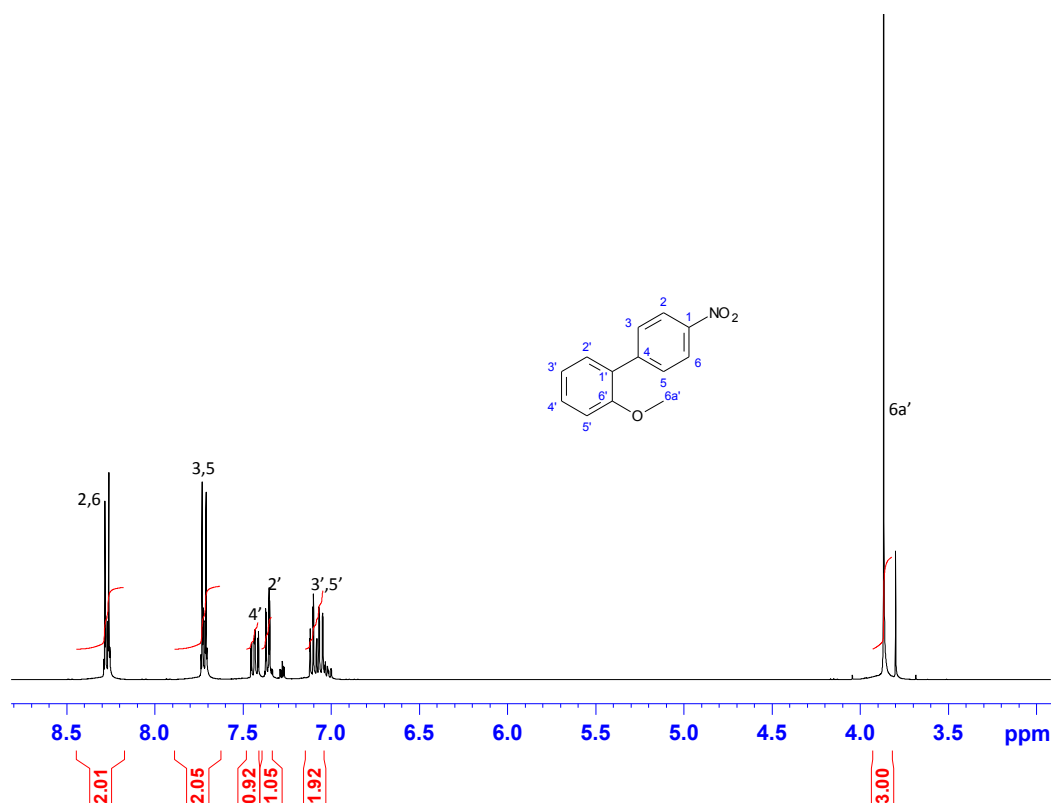
#### 4.5.2.3.6 Synthesis of 4-(2-methoxyphenyl)-nitrobenzene (269)

The cross-coupling reaction of 2-(2-methoxyphenyl)-benzo-1,3,2-diazaborolane (**179**) with 4-bromonitrobenzene (**261**) afforded 2-(methoxyphenyl)-nitrobenzene (**269**) in 85% yield based on NMR (**Scheme 99**). Purification of the title compound has proven laborious because the starting material (**179**) had a retention factor similar to that of the product.



### Scheme 99

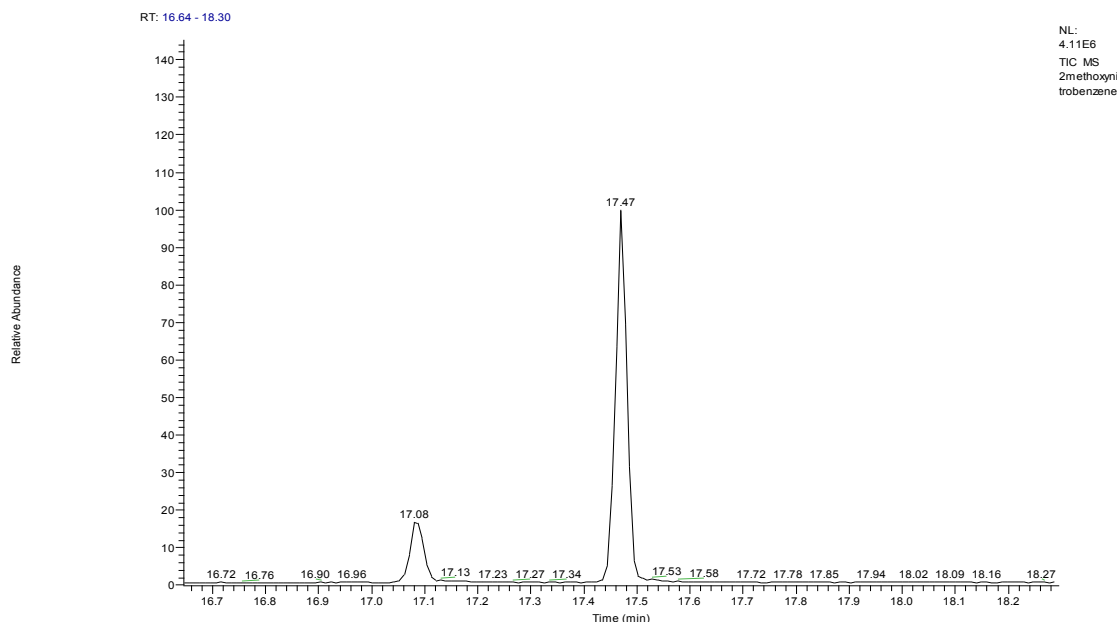
Attempted purification of the product using two consecutive radial chromatography discs was not successful. For this reason, it was difficult to remove the starting material and as a consequence, the yield of the desired product was based on the integration ratio of the  $^1\text{H}$  NMR. Despite the contamination of the desired product with the starting material, the  $^1\text{H}$  NMR spectrum revealed the product to be sufficiently clean and the assignments are consistent with the anticipated structure (**Figure 62**). It was, however, surprising to note that the melting point of the product was found in the range of 61-63°C which is similar to the range reported in literature,<sup>95</sup> despite the presence of the contamination.



**Figure 62:**  $^1\text{H}$  NMR spectrum for compound **269**.

As expected, the GC trace for the product (**Figure 63**) showed two peaks with a retention time of 17.08 minutes attributable to the starting material and the major peak

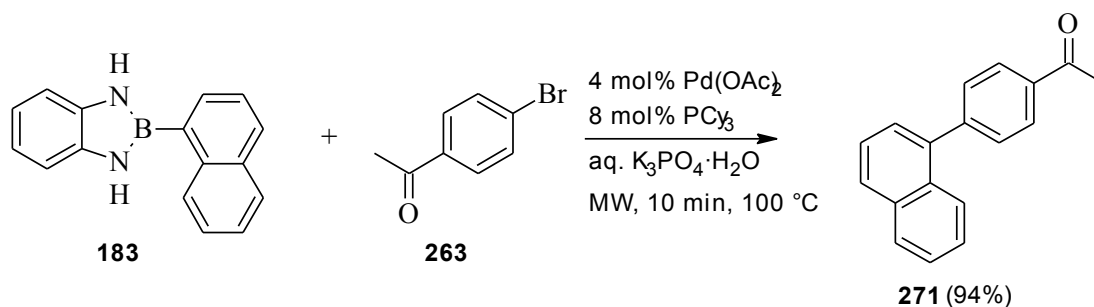
with a retention time of 17.47 minutes corresponding to the Suzuki coupled-product **269** (Figure 63). The infrared spectrum of the product shows the absorption bands at  $1231\text{ cm}^{-1}$  and  $1509\text{ cm}^{-1}$  which can be related to the stretching vibrations of the O-CH<sub>3</sub> and N-O bonds.



**Figure 63:** GC trace for compound **269**

#### 4.5.2.3.7 Synthesis of 1-[4-(1-naphthalenyl)]-ethanone (**270**)

2-(1-Naphthalenyl)-benzo-1,3,2-diazaborolane (**183**) was successfully coupled with 4-bromoacetophenone (**263**) to afford the desired coupled-product (**270**) in an isolated yield of 94% (Scheme 100). To confirm the structure of the product, spectroscopic data was collected and carefully analysed.



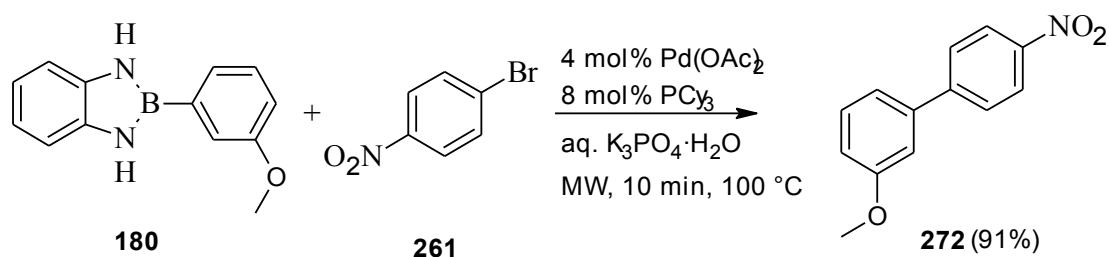
**Scheme 100**

The  $^1\text{H}$  NMR spectrum revealed the product to be clean as evident by the integral ratios corresponding to the expected number of protons. The purity of the coupled product was also reflected by the melting point of  $102\text{-}103^\circ\text{C}$  which is similar to melting point of  $102\text{-}103^\circ\text{C}$  reported in literature.<sup>95</sup> GC-MS analysis showed a peak

with a relative abundance of 100% which has a  $m/z$  value of 231 corresponding to the formation of  $[C_{17}H_{11}O]^+$  ion as a result of the fragmentation of the C–C bond adjacent to the carbonyl group. The infrared spectrum confirmed the presence of the carbonyl functionality as evident with the appearance of an absorption band at  $1681\text{ cm}^{-1}$  which corresponds to the stretching vibration of the C=O bond.

#### 4.5.2.3.8 Synthesis of 4-(3-methoxyphenyl)-nitrobenzene (272)

4-(3-Methoxyphenyl)-nitrobenzene (**272**) was achieved in an excellent 91% yield when 2-(3-methoxybiphenyl)-benzo-1,3,2-diazaborolane (**179**) was coupled with 4-bromonitrobenzene (**261**) under the optimised reaction conditions as described above (Scheme 101).

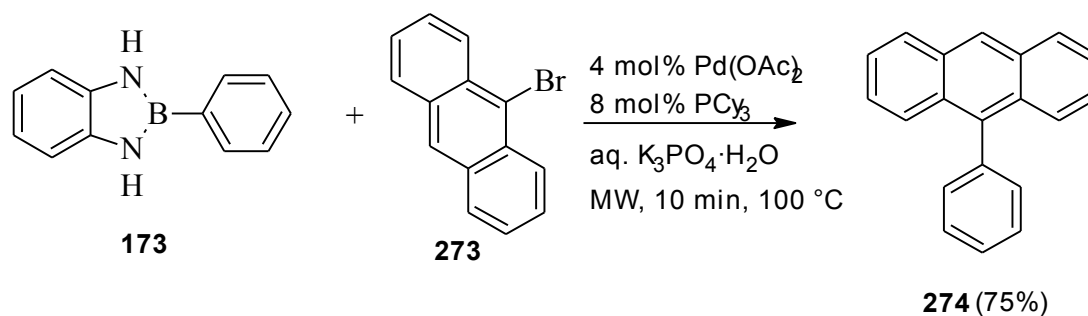


Scheme 101

The  $^1\text{H}$  and  $^{13}\text{C}$  NMR spectra were carried out and assigned accordingly. GC-MS analysis showed a peak with natural abundance of 100% corresponding to the molecular mass of 229 as expected for the desired product. The product was obtained as a white amorphous powder.<sup>99</sup>

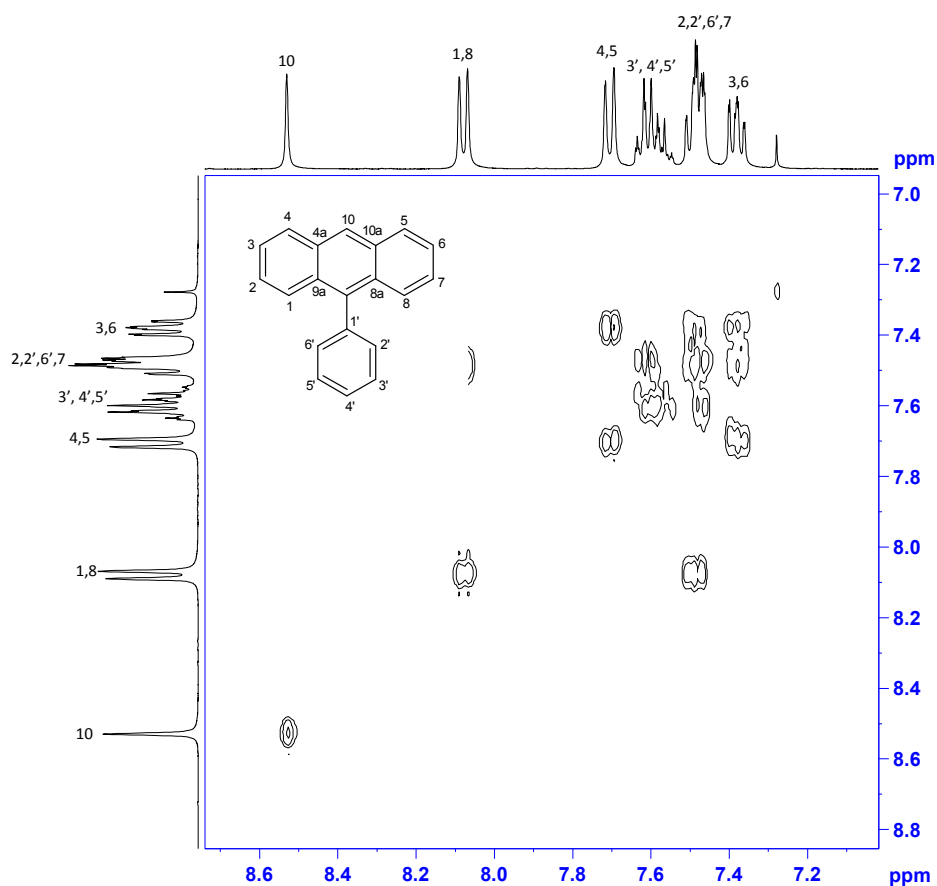
#### 4.5.2.3.9 Synthesis of 9-phenylanthracene (273)

The cross-coupling reaction between 2-phenylbenzo-1,3,2-diazaborole (**173**) with 9-bromoanthracene (**273**) mediated by  $\text{Pd(OAc)}_2/\text{PCy}_3$  combination under the representative procedure B furnished the title product, after purification through silica gel, as colourless plates-like crystals in 75% yield (Scheme 102).



Scheme 102

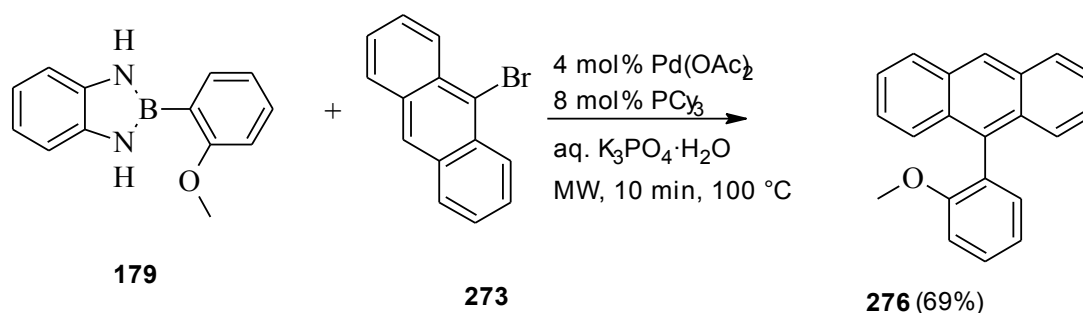
The COSY spectrum of the title compound displayed six different protons as illustrated on figure 75 below. The melting point was found in the range 155-157 °C which is close to the reported melting point range of 153-155 °C.<sup>106</sup>



**Figure 64: COSY spectrum for compound 274**

#### 4.5.2.3.10 Synthesis of 9-(2-methoxyphenyl)-anthracene (275)

2-(Methoxyphenyl)-benzo-1,3,2-diazaborole (**179**) was smoothly coupled with 9-bromonanthracene (**273**) as an electrophilic coupling partner to afford the coupled-product **275** in 72% yield following representative procedure B. After purifying the crude product, the desired product was obtained as cream-white amorphous powder whose <sup>1</sup>H and <sup>13</sup>C NMR spectra revealed the expected proton and carbon peaks which are consistent with anticipated structure.

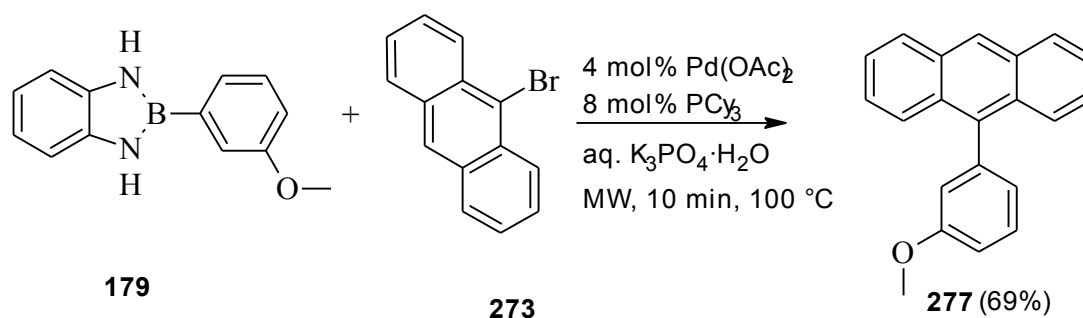


**Scheme 103**

GC-MS also confirmed the product as evident by the molecular peak  $[\text{M}^+]$  at 284 which is consistent with the calculated molar mass of the product. The melting point was found in the range of 177-178 °C (lit.<sup>107</sup>: 177-179 °C).

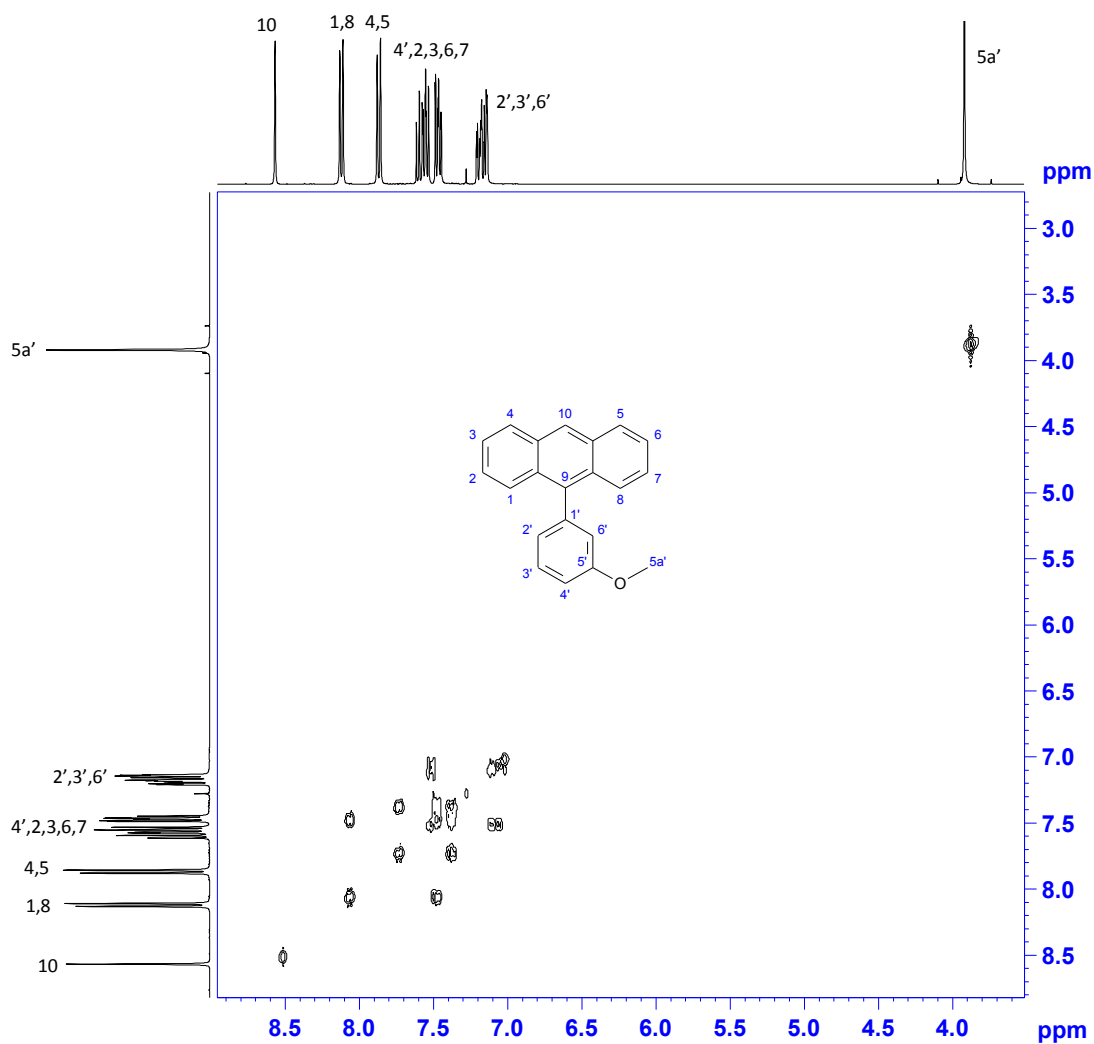
#### 4.5.2.3.11 Synthesis of 9-(3-methoxyphenyl)-anthracene (277)

9-Bromoanthracene (**273**) was successfully coupled with 2-(3-methoxyphenyl)-benzo-1,3,2-diazaborole (**180**) following the representative procedure B. The title compound was obtained as colourless crystals in 69% after the purification of the crude product (**Scheme 104**).



**Scheme 104**

The  $^1\text{H}$  and  $^{13}\text{C}$  NMR spectra of the obtained crystals are consistent with the anticipated structure confirming the successful preparation of **277**. The COSY spectrum for the title compound was also consistent with the anticipated structure and is depicted in figure 4.12. The melting point of the crystals was recorded in the range of 99-101 °C (lit.<sup>108</sup>: 99-100 °C).



**Figure 65.** COSY spectrum for compound 277.

The COSY spectrum showed seven different resonances (**Figure 65**). The single integrating for three protons at  $\delta$  3.92 ppm was assigned to the methoxy group. The multiplet integrating for three protons whose signal appears in the range  $\delta$  7.13-7.21 ppm were assigned to protons 2'-H, 3'-H and 6'-H. The multiplets in the close range of  $\delta$  7.33-7.41 ppm and  $\delta$  7.44-7.55 ppm were assigned to 2-H, 3-H, 4'-H, 6-H and 7-H. The doublets resonating at  $\delta$  7.73 ppm and  $\delta$  8.06 ppm were assigned to protons 4-H, 5-H and 1-H, 8-H, respectively (**Figure 65**).

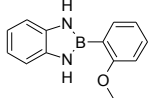

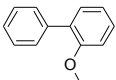
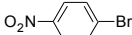
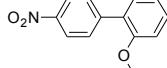
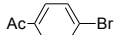
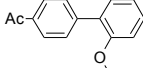
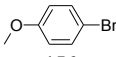
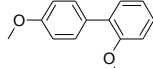
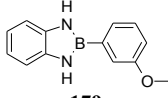
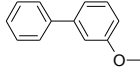
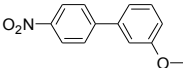
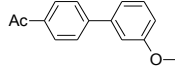
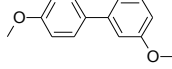
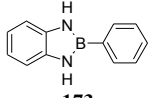
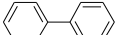
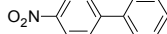
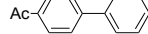
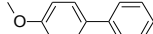
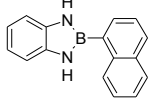
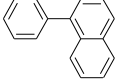
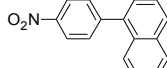
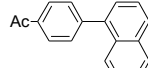
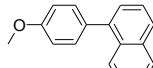
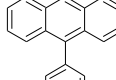
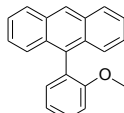
### **4.5.3 Summary of the Suzuki-Miyaura Cross-Coupling Reaction.**

In this section, the synthesised 2-arylbenzo-1,3,2-diazaborolane compounds were evaluated as potential Suzuki coupling partners. A range of aryl bromides bearing both electron-withdrawing and donating substituent were coupled with 2-arylbenzo-1,3,2-diazaborolane compounds under optimised reaction conditions to afford the substituted biphenyls in isolated yields ranging from 62-96% in only 10 minutes (**Table 4.2**).

The yields of substituted biphenyl products obtained in this project were compared with those achieved from the use of boronic acids as coupling partners and in most cases were shown to be significantly superior. 2-Arylbenzo-1,3,2-diazaborolane derivatives seems to be better Suzuki coupling partners than the boronic acids counterparts.



**Table 4.2.** Summary of Palladium-Catalyzed Suzuki-Miyaura Cross-Coupling Reaction.

Entry	diazaborolane	aryl bromide	conditions	product	% Yields
1	 <b>179</b>	 <b>252</b>	<b>A</b>		68
2		 <b>261</b>	<b>B</b>		85
3		 <b>263</b>	<b>B</b>		86
4		 <b>156</b>	<b>A</b>		65
5	 <b>179</b>	<b>252</b>	<b>A</b>		72
6		<b>261</b>	<b>B</b>		91
7		<b>263</b>	<b>B</b>		83
8		<b>156</b>	<b>A</b>		76
9	 <b>173</b>	<b>252</b>	<b>A</b>		88
10		<b>261</b>	<b>B</b>		91
11		<b>263</b>	<b>B</b>		90
12		<b>156</b>	<b>A</b>		62
13	 <b>183</b>	<b>252</b>	<b>A</b>		85
14		<b>261</b>	<b>B</b>		96
15		<b>263</b>	<b>B</b>		94
16		<b>156</b>	<b>A</b>		68
17	<b>173</b>	<b>273</b>	<b>B</b>		75
18	<b>179</b>	<b>273</b>	<b>B</b>		72

#### 4.5.4 Conclusion

A range of 2-arylbenzo-1,3,2-diazaborolane compounds were synthesised from the cyclocondensation of boronic acids with 1,2-diaminobenzene in isolated yields ranging from 71 to 98%.

With 2-arylbenzo-1,3,2-diazaborolane compounds in hand, their efficiency and versatility as Suzuki coupling partners were evaluated. The coupling reaction between 2-phenylbenzo-1,3,2-diazaborolane and bromobenzene was conducted under different palladium catalysts in order to optimise the reaction conditions. The optimal conditions were shown to be the combination of  $\text{Pd}(\text{OAc})_2$ ,  $\text{PCy}_3$  and aqueous  $\text{K}_3\text{PO}_4 \cdot \text{H}_2\text{O}$  for the synthesis of biphenyls.

Under these reaction conditions, several aryl bromides bearing electron-donating and withdrawing substituents were successfully coupled with 2-arylbenzo-1,3,2-diazaborolane compounds to afford antisymmetrical and symmetrical biphenyls in isolated yields ranging from 62-96% in 10 minutes. Substrates bearing electron-withdrawing substituents were shown to be more reactive under these reaction conditions affording biphenyls in excellent isolated yields ranging from 83% to 96%. While our yields are comparable with the yields reported in literature, our reactions take only 10 minutes (!) compared to many hours of reflux as reported in the literature.

These studies highlights a novel methodology for the preparation of both the symmetrical and antisymmetrical biphenyls from 2-arylbenzo-1,3,2-diazaborolane derivatives as potential Suzuki coupling partners. These results have been drawn up for the publication in journal of organic chemistry. For reference, a draft copy of the publication is attached below.

## 4.6References

1. Frankland, E., Duppa, B. F., *JustusLiebigs Ann. Chem.* **1860**, 115, 319.
2. Kimpe, D., N., Keppens, M., Froneg, G., *Chem. Commun.* **1996**, 635.
3. Spencer, J., Burd, A. P., Goodwin, C. A., Marette, S. A. M., Scully, M. F., Adatia, T., Deadman, J. J., *Tetrahedron* **2002**, 58, 1551.
4. Brown, G. J., Silva, A. P., Pagliari, S., *J. Am. Chem. Soc.* **2002**, 2461.
5. Georgiou, I., Ilyashenko, G., Wthiting, A., *Acc. Chem. Res.* **2009**, 42, 756.
6. Hall, D. G., *Boronic acids: Preparation and Application in Organic Synthesis and Medicine*. VCH, Weinham., 2005; p 1-99.
7. Melamed, M., Khotinsky, E., *Chem. Ber.* **1909**, 42, 3090.
8. Johnson, J. R., Seaman, W., *J. Am. Chem. Soc.* **1931**, 53, 711.
9. Cladingboel, D. E., *Org. Res. Devel.* **2000**, 4, 153.
10. Zenk, R., Partzsch, S., *Chim. Oggi.* **2003**, 70.
11. Blatch, A. J., Chetina, O. V., Howard, J. A. K., Patric, L. G. F., Smethurst, C. A., Whiting, A., *Org. Biomol. Chem.* **2006**, 4.
12. Wong, K.-T., Chien, T.-T., Liao, Y.-L., Lin, C.-C., Chou, M.-Y., Leung, M.-K., *J. Org. Chem.* **2002**, 67, 1041.
13. Garg, N. K., Sarpong, R., Stoltz, B. M., *J. Am. Chem. Soc.* **2002**, 124, 13179.
14. Lauer, M., Wulff, G., *J. Organomet. Chem.* **1983**, 256, 1.
15. Sharp, M. J., Snieckus, V., *Tetrahedron Lett.* **1985**, 49, 5997.
16. Larsen, R. D., King, A. O., Chen, C. Y., *J. Org. Chem.* **1994**, 59, 6391.
17. Ishiyama, T., Miyaura, N., *Chem. Rec.* **2004**, 3, 271.
18. Billingsley, K., Barder, T. E., Buchwald, S. L., *Angew. Chem. Int. Ed.* **2007**, 46, 5359.
19. Zhu, W., Ma, D., *Org. Lett.* **2006**, 8, 261.
20. Rosen, M. B., Huang, C., Percec, V., *Org. Lett.* **2008**, 10, 2597.
21. Rosen, M. B., Percec, V., Wilson, D. A., Wilson, C. J., , *Org. Lett.* **2008**, 10, 4879.
22. Moldoveanu, C., Wilson, D. A., Wilson, C. J., Corcoran, P., Rosen, B. M., Percec, V., *Org. Lett.* **2009**, 11, 4974.
23. Knochel, P., Gavvryushin, A., *Synfacts* **2010**, 1, 84.
24. Wilson, D. A., Wilson, C. J., Moldoveanu, C., Resmerita, A.-M., *J. Am. Chem. Soc.* **2010**, 132, 1800.
25. Moldoveanu, C., Wilson, D. A., Wilson, C. J., Corcoran, P., Rosen, B. M., Percec, V., *J. Org. Chem.* **2010**, 75, 5438.
26. Leowanawat, P., Resmerita, A.-M., Moldoveanu, C., Liu, C., Zhang, N., *J. Org. Chem.* **2010**, 75, 7822.
27. Broutin, E.-P., Cerna, I., Campaniello, M., Leroux, F., Colobert, F., *Org. Lett.* **2004**, 24, 4419.
28. Murata, M., Sambommatsu, T., Watabane, S., Masuda, Y., *Synlett.* **2006**, 1867.
29. Billingsley, K. B., S. L., *J. Org. Chem.* **2008**, 73, 5589.
30. Thery, A., Gueiffier, A., *Eur. J. Org. Chem.* **2008**, 4824.
31. Zhou, W.-J., Wang, H.-K., Wang, J.-X., *J. Org. Chem.* **2009**, 74, 5599.
32. Chemler, S. R., Trauner, D., Dinishefsky, S. J., *Angew. Chem. Int. Ed.* **2001**, 40, 4544.
33. Yasuda, N., *J. Organomet. Chem.* **2002**, 253, 279.
34. Zhou, W.-J., Wang, H.-K., Wang, J.-X., *Eur. J. Org. Chem.* **2010**, 416.
35. Heck, R. F., *J. Am. Chem. Soc.* **1968**, 90, 5518.
36. Heck, R. F., *J. Am. Chem. Soc.* **1968**, 90, 5526.
37. Heck, R. F., *J. Am. Chem. Soc.* **1968**, 90, 5536.
38. Heck, R. F., *J. Am. Chem. Soc.* **1968**, 90, 5542.
39. Stille, K. J., Scott, J. W., *J. Am. Chem. Soc.* **1986**, 108, 3033.
40. Stille, K. J., Scott, J. W., Crisp, G. T., *J. Am. Chem. Soc.* **1984**, 106, 4630.
41. Miyaura, N., Suzuki, A., *Chem. Rev.* **1995**, 95, 2457.

42. Buchwald, S. L., Martin, R., *Chem. Res.* **2008**, 41, 1461.
43. Suzuki, A., Yamada, K., Miyaura, N., *Tetrahedron Lett.* **1979**, 20, 3437.
44. Brennfuhrer, A., Nuemann, H., Beller, M., *Angew. Chem. Int. Ed.* **2009**, 48, 4114.
45. Marion, N., Nolan, S. P., *Acc. Chem. Res.* **2008**, 41, 1440.
46. Kingston, J. V., Verkade, J. G., *J. Org. Chem.* **2007**, 72, 2816.
47. He, Y., Cai, C., *Cat. Comm.* **2011**, 12, 678.
48. Suzuki, A., Yanagi, T., Miyaura, N., *Synth. Commun.* **1981**, 11, 513.
49. Wright, S. W., Hageman, D. L., McClure, D. L., *J. Org. Chem.* **1981**, 59, 6095.
50. Watanabe, T., Miyaura, N., Suzuki, A., *Synlett.* **1992**, 207.
51. Zhang, H., Chan, K.S., *Tetrahedron Lett.* **1996**, 37, 1043.
52. Dreher, D. S., Lim, S.-Ee., Sandrock, L.D, Molander, G. A., *J. Am. Chem. Soc.* **2009**, 74, 3626.
53. Cheng, J., Wang, F., Xu, H.-J., Pan, Y., Zhang, Z., *Tetrahedron Lett.* **2003**, 44, 7095.
54. Bellina, F., Carpita, A., Rossi, R., *Synthesis* **2004**, 2419.
55. Pan, C., Liu, M., Zhang, Wu, H., Ding, J., Cheng, J., *Cat. Comm.* **2008**, 9, 508.
56. Korolven, D. N., Bumagin, N. A., *Tetrahedron Lett.* **2006**, 47, 4225.
57. Andrio, A. L., Nguyen, N. B., Guilera, G., Livingston, G. A., Hii, K. K., *Catal. Sci. Technol.* **2012**, 2, 316.
58. Kantam, M. L., Subhas, M. S., Roy, S., Roy, M., *Synlett.* **2006**, 633.
59. Trzeciak, A. M., Ziolkowski, J., *Coord. Chem. Rev.* **2007**, 251, 1281.
60. Martins, D., de L., Alvarez, M. H., Aguiar, C. S. L., *Tetrahedron Lett.* **2010**, 51, 6814.
61. Astruc, D., *In Nanoparticles and Catalysis; Wiley-VCH: Weinheim*, 2008; Vol. 1, p 1.
62. Lorenzo, P. M., *J. Phys. Chem. Lett.* **2012**, 3, 167.
63. Percec, V., Bae, Y.-J., Hill, H. D., *J. Org. Chem.* **1995**, 60, 1060.
64. Zim, D., Monteiro, L. A., Lando, R. V., Dupont, J., *Org. Lett.* **2001**, 3, 3049.
65. Zim, D., Monteiro, L. A., *Tetrahedron Lett.* **2002**, 43, 4009.
66. Lee, C.-C., Ke, W., Chan, T.-K., Lai, C.-L., Hu, H.-C., Lee, M. H., *Chem. Eur. J.* **2077**, 13, 582.
67. Chen, C., Yang, M.-L., *Tetrahedron Lett.* **2007**, 48, 2427.
68. Tang, Y.-Z., Hu, Q.-S., *J. Am. Chem. Soc.* **2004**, 126, 3058.
69. Inamoto, K., Kuroda, J.-I., Kwon, E. Hiroya, K., Doi, T., *J. Organomet. Chem.* **2009**, 694, 389.
70. Tu, T., Mao, H., Herbert, C., Xu, M., Dotz, K. H., *Chem. Commun.* **2010**, 46, 7796.
71. Fan, H.-X., Yang, L.-M., *Eur. J. Org. Chem.* **2010**, 2457.
72. Bellina, F., Cauteruccio, S., Rossi, R., *Curr. Org. Chem.* **2008**, 12, 774.
73. Pu, L., *Chem. Rev.* **1998**, 98, 2405.
74. Wallow, T. I., Novak, B. M., *J. Org. Chem.* **1994**, 59, 5034.
75. Molander, G. A., Beaumard, F., *Org. Lett.* **2010**, 12, 4022.
76. Molander, G. A., Canturk, B., *Angew. Chem. Int. Ed.* **2009**, 48, 9240.
77. Molander, G. A., Canturk, B., Kennedy, L. E., *J. Org. Chem.* **2009**, 74, 973.
78. Knapp, D. M., Gills, E. P., Burke, M. D., *J. Am. Chem. Soc.* **2009**, 131, 6961.
79. Suzuki, A., Yamada, K., Miyaura, N., Suginome, H., *J. Am. Chem. Soc.* **1985**, 107, 972.
80. Kochi, J. K., *Organometallic Mechanisms and Catalysis*, . Academia, New York, 1978.
81. Hegedus, L. S., *Organometallic in Organic Synthesis*, . Schosser. Wiley, New York, , 1994.
82. Soderquist, J. A., Matos, K., *J. Org. Chem.* **1998**, 63, 461.
83. Miyaura, N., Suzuki, A., Yamada, K., *Tetrahedron Lett.* **1979**, 20, 3437.
84. (a) Hadebe, S. W., Robinson, R. S., *Eur. J. Org. Chem.* **2006**, 4898. (b) Denk, M. K. K., *Compounds of Boron and Aluminium*, Chapter 3, web: [http://131.104.156.23/Lectures/331/331 Chapter 3.html](http://131.104.156.23/Lectures/331/331%20Chapter%203.html) [ Date of access is 22 August 2013]

85. Schweizer, S., Eickhoff, D., Brockhinke, R., Cherian, D., Weber, L., Brockhinke, A., *Phys. Chem. Chem. Phys.* **2011**, 13, 9301.
87. Thilanger, P.; Narayanan, S. R.; Chandrasekhar, V., *Organometallics*. **2009**, 28, 5882-5888.
88. Zhang, L., Wang, L., Li, H., Li, P., *Synth. Commun.* **2008**, 38, 1498.
89. Bezier, D., Darcel, C., *Adv. Synth. Catal.* **2009**, 351, 1732.
90. Desmarets, C., Oma-A., R., Walcarius, A., Lambert, J., Champagne, B., Fort, Y., Schnieder, R., *tetrahedron* **2008**, 64, 372.
91. Truce, W., E., Tate, D. P., Burdge, D. N., *J. Am. Chem. Soc.* **1960**, 82, 2872.
92. Quasdorf, W. K., Rieher, M., Petrova, V. K., Garg, K. N., *J. Am. Chem. Soc.* **2009**, 131, 17748.
93. Wang, L., Lu, W., *Org. Lett.* **2009**, 11, 1079.
94. Chandrasekhar, V., Thilanger, P., Narayanan, S. R., *Organometallics* **2009**, 28, 5882.
95. Qin, C., Lu, W., *Org. Lett.* **2008**, 73, 7424.
96. Snieckus, V., Blackburn, T., Finch, A.-A., *J. Am. Chem. Soc.* **2009**, 131, 17750.
97. Wei, J.-F., Jiao, J., Feng, J.-J., Lv, J., Zhang, X.-R., Shi., X.-Y., Zhan-G., *J. Org. Chem.* **2009**, 6283.
98. Marcuccio, S. M., Dannock, M. C., O'Keefe, D. F., *Tetrahedron Lett.* **1992**, 33, 6679.
99. Seganish, W. M., DeShong, P., *J. Org. Chem.* **2004**, 69, 6790.
100. Itoh, Y., Brossi, A., Hamel, E., Lun, C. M., *Helvetica Chimica Acta* **1988**, 71, 1199.
101. Schweizer, S., Becht, M.-J., Drian, L. D., *Tetrahedron* **2010**, 66, 765.
102. Malanesi, S., Fagoni, S., Albini, P., *J. Org. Chem.* **2005**, 70, 603.
103. Metallinos, C., Barrett, F. B., Chaytor, J. L., Heska, M. E. A., *Org. Lett.* **2004**, 6, 3641.
104. Saito, S., Oh-tani, S., Miyaura, N., *J. Org. Chem.* **1997**, 62, 8024.
105. Zhang, G., *Chem. Research.* **2004**, 9, 593.
106. Nakamichi, N., Kawabota, H., Hayashi, M., *J. Org. Chem.* **2003**, 68, 8272.
107. Yashuba, T., Hiroyuku, W., Michiyo, N., Tetsuya, S., Masahiro, M., Masakatsu, N., *J. Org. Chem.* **2003**, 68, 5236.
108. Dikerman, C. S., Klain, M. V., George, B., *J. Org. Chem.* **1964**, 29, 3639.

# Chapter Five

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## 5. Experimental

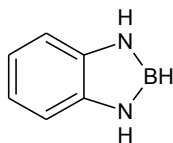
### 5.1 Chemical and Instrumental:

All reaction were carried out under nitrogen and/or argon atmosphere in an oven-dried glassware containing a magnetic stirrer bar and dry septum. Toluene was freshly distilled from Na/benzophenone prior to use. All arylboronic acids were prepared according previously published literature methods.<sup>1,2</sup> Microwave reactions were performed in a CEM Discover synthetic microwave using a 10 cm microwave tube equipped with a magnetic stirrer bar and reaction vessel cap. <sup>1</sup>H NMR (400 MHz), <sup>13</sup>C NMR (100 MHz) and <sup>11</sup>B NMR (128 MHz) were recorded on a Bruker Avance III 400 (9.4 T) spectrometer in a normal glass NMR tubes. All the NMR spectra were recorded as solution in specified deuterated solvents and are reported in parts per million (ppm) downfield from tetramethylsilane (TMS) as internal standard. <sup>11</sup>B NMR spectra were referenced to BF<sub>3</sub>:OEt<sub>2</sub> (External, neat, with capillary tube of acetone-d<sub>6</sub> for the deuterium lock). Melting points were measured on a Reichert Austria apparatus using 22×22 mm deck Glaser and are uncorrected.

High-resolution mass spectra (HRMS) were obtained on a Waters Acquits LCT premier (TOF) ultra-performance liquid chromatography-mass spectrometry. Low resolution (Electron Impact) mass spectra were acquired on a Thermo Finnigan trace GC, coupled with a Polaris Q mass spectrometer. UV studies were conducted on CARRY 100 Bio UV visible spectrometry in specified solvents. Infrared was recorded using ID, Fourier Transform Infrared instrument. Samples were placed on a diamond and compressed with infrared pressure steel. Purifications of the products were performed by centrifugal preparative thin-layer chromatography (chromatotron) and flash column chromatography on Merk silica gel cat. No. 1.07749 and Fluka silica gel 60 cat No.70-230 mesh (0.063-0.2mm), respectively.

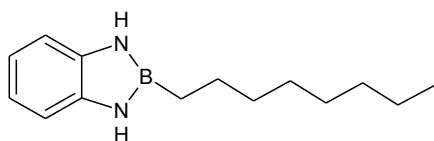
## 5.2 EXPERIMENTAL FOR CHAPTER TWO

### 5.2.1 Synthesis of 2-Benzo-1,3,2-dizaborolane (79)



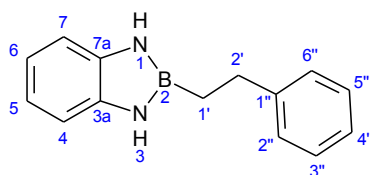
1,2-Diaminobenzene (0.54 g, 5.00 mmol) was dissolved in dichloromethane (5.0 ml) in a flame dried round-bottomed flask. After complete dissolution of the solid, borane-dimethyl sulphide complex (5.0 ml, 5.00 mmol) was introduced dropwise through the septum. The resulting mixture was stirred under reflux for 5 hrs under a dry atmosphere of nitrogen. Benzo-1,3,2-diazaborolane was obtained as a clear liquid (95%, based on  $^{11}\text{B}$  NMR analysis).  $^{11}\text{B}$  NMR (160 MHz,  $\text{BF}_3 \cdot \text{OEt}_2$ ):  $\delta$  ppm 23.9 (d,  $J = 153.2$  Hz,  $^1\text{H}$ , BH).

### 5.2.2 Synthesis of 2-octyl-benzo-1,3,2-diazaborolane (81). General method A.



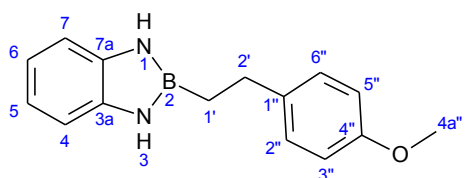
A freshly prepared benzo-1,3,2-diazaborolane solution (20.0 ml, 46.2 mmol) in DCM was injected in an oven-dried, nitrogen purged two neck round bottomed flask, followed by 1-octene (7.3 ml, 46.2 mmol) with continuous stirring. To this solution was added the DCM solution of Wilkinson catalyst (2.0 mol%, 855 mg), which was prepared in a separate flame-dried, and nitrogen flushed flask. The reaction mixture was stirred at 25 °C for 24 hr followed by the evaporation of the volatiles. The resulting orange-yellow oily product was subjected to flash column chromatography using hexane as eluting solvent. The title compound was obtained as orange-yellow wax (92%), mp 26.2-28.9 °C.  $^{11}\text{B}$  NMR (160 MHz,  $\text{BF}_3 \cdot \text{OEt}_2$ ):  $\delta$  ppm 31.6 (s). Ms (IE):  $m/z$  (%) 231[ $\text{M}^+$ ] (18), 230 (100), 229 (15), 145 (15), 132 (16), 119 (17), 118 (31).

### 5.2.3 Synthesis of phenethyl-benzo-1,3,2-diazaborolane (74)



Following general method A, the title compound (**74**) was synthesised from the reaction of benzo-1,3,2-diazaborolane (20.0 ml, 46.2 mmol) with styrene (5.3 ml, 46.2 mmol) and the reaction mixture was heated at *ca.* 60 °C for 48 hrs. Compound **74** was obtained as a cream powder in 81% after purification. Recrystallisation of the product from hexane afforded colourless needle-like crystals, melting point 53-54 °C.  $^{11}\text{B}$  NMR (160 MHz,  $\text{BF}_3 \cdot \text{OEt}_2$ ):  $\delta$ ppm 31.2 (s).  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ ):  $\delta$ ppm 1.49 (t,  $J = 7.9$  Hz, H-1', 2H), 2.80 (t,  $J = 8.1$  Hz, H-2', 2H), 6.18 (s, H-1,3, 2H), 6.77-6.81 (m, H-5,6, 2H), 6.82-6.87 (m, H-4,7, 2H), 7.09-7.25 (m, H-2'' to H-6'', 5H).  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ ):  $\delta$ ppm 31.9 (C-1',2'), 110.4 (C-4,7), 118.9 (C-5,6), 125.7 (C-3'',5''), 128.0 (C-4''), 128.4 (C-2'', 6''), 136.1 (C-3a, 7a), 144.3 (C-1''). MS (EI):  $m/z$  (%) 233 [ $\text{M}^+$ ] (16), 222 (100), 221 (27), 132 (17), 131 (44), 118 (29). HSMS found [ $\text{M}^+$ ] 221.1247, calculated for  $\text{C}_{14}\text{H}_{14}\text{N}_2\text{B}$  221.1250. IR (neat), 3385, 3364, 3027, 1621  $\text{cm}^{-1}$ .

### 5.2.4 Synthesis of 2-{2-(4-methoxyphenyl)-ethyl}-benzo-1,3,2-diazaborolane (75).

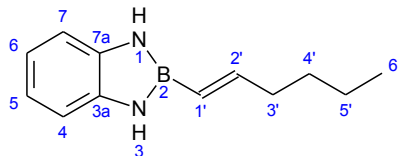


Following general method A, benzo-1,3,2-diazaborolane (20.0 ml, 46.2 mmol) was reacted with 4-vinylanisole (5.61 ml, 46.2 mmol) at *ca.* 60 °C for 60 hrs. The title compound was obtained as a cream-white powder (79%), mp 128-130 °C.  $^{11}\text{B}$  NMR (160 MHz,  $\text{BF}_3 \cdot \text{OEt}_2$ ):  $\delta$  ppm 31.2 (s).  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ ):  $\delta$  ppm 4.56 (t,  $J = 8.1$  Hz, H-2', 2H), 2.85 (t,  $J = 8.0$  Hz, H-1', 2H), 3.82 (s, H-4a'', 3H), 6.29 (s, H-1,3, 2H), 6.87 (d,  $J = 8.5$  Hz, H-3'',5'', 2H), 6.90-6.94 (m, H-5,6, 2H), 6.98-7.03 (m, H-4,7, 2H), 7.19 (d,  $J = 8.8$  Hz, H-2'', 6'', 2H).  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ ):  $\delta$ ppm 30.9,



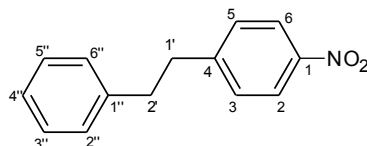
55.2, 110.5, 113.5, 140.0, 118.8, 128.8, 136.0, 136.3, 157.7. HRMS found: 251.1360  $[M^+]$ , calculated for  $C_{15}H_{17}BN_2$  is 251.1356.

### 5.2.5 Synthesis of 2-(1*E*-hexenyl)-benzo-1,3,2-diazaborolane (**86**)



1*E*-1-hexenyl-boronic acid was prepared according to known procedures.<sup>f</sup> A round bottom flask, equipped with a Dean and Stark apparatus, magnetic stirrer bar and reflux condenser, was charged with freshly prepared 1*E*-1-hexenyl-boronic acid (0.40 g, 0.31 mmol), phenylenediamine and toluene (20 ml). The resulting mixture was heated to reflux for 1h, followed by the evaporation of the solvent in *vacuo* to afford light-brown solid, which after purification through column-chromatography, afforded the title compound (**86**) as fluffy white amorphous solid (78%), mp 45-47 °C. <sup>11</sup>B NMR (160 MHz,  $BF_3 \cdot OEt_2$ ):  $\delta$  ppm 27.2 (s). <sup>1</sup>H NMR (400 MHz,  $CDCl_3$ ):  $\delta$  ppm 0.93 (t,  $J=7.3$  Hz, H-6', 3H), 1.33-1.52 (m, H-4', 5', 4H), 2.19-2.27 (m, H-3', 2H), 5.88 (dt,  $J=18.1, 7.6$  Hz, H-2', 1H), 6.51 (dt,  $J=18.3, 7.5$  Hz, H-1', 1H), 6.77-6.84 (m, H-5,6, 2H), 6.98-7.05 (m, H-4,7, 2H), 7.87 (s, H-1,3, 2H). <sup>13</sup>C NMR (100 MHz,  $CDCl_3$ ):  $\delta$  ppm 13.3 (C-6'), 21.9 (C-5'), 30.9 (C-4'), 35.6 (C-3'), 110.5 (C-4,7), 118.2 (C-5,6), 137.1 (C-3a, 7a), 148.0 (C-2'). IR (neat) 3381, 3360, 2961, 2928, 2874, 2856, 1634  $cm^{-1}$ . HRMS found  $[M^+]$  199.1404, calculated for  $C_{12}H_{17}BN_2$  is 199.1407.

### 5.2.6 Synthesis of 1-(4-nitrophenyl)-2phenethane (**91**)

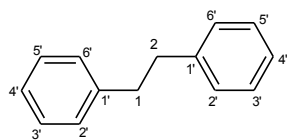


**General method B:** A microwave tube equipped with a magnetic stirrer bar was charged with 4-bromonitrobenzene (0.10 g, 0.49 mmol),  $K_3PO_4 \cdot H_2O$  (0.34 g, 1.47 mmol),  $PCy_3$  (11 mg, 0.039 mmol),  $Pd(OAc)_2$  (4.40 mg, 0.020 mmol),

<sup>f</sup> Saito, S., Oh-tani, S., Miyaoura, N. *J. Org. Chem.* **1997**, 62, 8024.

2-phenethylbenzo-1,3,2-diazaborolane (0.22 g, 0.98 mmol) and toluene (0.1 ml). The reaction tube was closed with a microwave cap and irradiated with microwave energy (200W) for 15 min. After the completion of the reaction, the black resulting mixture was dissolved in acetone and filtered. The evaporation of the volatiles resulted in a black oily residue, which when purified through a column chromatography, using hexane:ethylacetate (8:2), afforded compound **2.5** as colourless crystals (57%), mp 55-56 °C. <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>): δppm 2.98 (t, *J* = 7.7 Hz, H-1', 2H), 3.05 (t, *J* = 7.7 Hz, H-2', 2H), 7.15 (d, *J* = 7.6 Hz, H-4,5, 2H), 7.23 (t, *J* = 6.9 Hz, H-4'', 1H), 7.27-7.33 (m, H-2'', 4'', 5'' and 6'', 4H), 8.14 (d, *J* = 8.6 Hz, H-2,6, 2H). <sup>13</sup>C NMR (100 MHz, CDCl<sub>3</sub>): δppm 37.2, 37.6, 123.6, 128.5, 129.4, 140.5, 146.5, 149.4. HRMS found [M<sup>+</sup>+Na<sup>+</sup>] 250.0847, calculated for C<sub>14</sub>H<sub>13</sub>NNaO<sub>2</sub> is 250.0844.

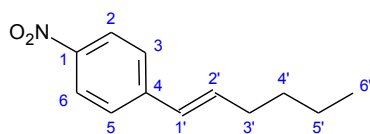
### 5.2.7 Synthesis of 1,1'-dibenzyl (93)



Following general method B, 2-phenethylbenzo-1,3,2-diazaborolane (0.11 g, 0.49 mmol) was reacted with bromobenzene (0.1 ml) to afford, after purification of the crude product, the title compound **2.6** as colourless crystals (79%) mp 51°C [lit.<sup>g</sup> 51 °C]. <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>): δppm 2.95 (s, H-1,2, 4H), 7.18-7.25 (m, H-2' to H-6', 5H), 7.26-7.34 (m, H-2' to H-6', 5H). <sup>13</sup>C NMR (100 MHz, CDCl<sub>3</sub>): δppm 37.9 (C-1,2), 125.9 (C-4'), 138.2 (C-2',6'), 138.3 (C-3',5'), 141.8 (C-1'). MS (EI): *m/z* (%) 65 (24), 91 (100), 92 (7), 104 (22), 182 (32) [M<sup>+</sup>].

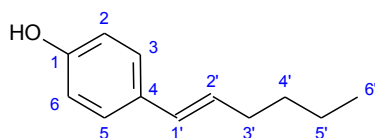
<sup>g</sup> Jourdent, A., Conzalez-Zamara, E., Zhu, J. *J. Org. Chem.* **2002**, 67, 3163.

### 5.2.8 Synthesis of 4-(1*E*-hexenyl)-nitrobenzene (**91**)



**General Method C:** A microwave tube equipped with a magnetic stirring bar was charged with 2-(1*E*-hexenyl)-benzo-1,3,2-diazaborolane (**91**) (0.20 g, 0.10 mmol),  $K_3PO_4 \cdot H_2O$  (0.35 g, 1.50 mmol),  $PCy_3$  (11.2 g, 0.040 mmol),  $Pd(OAc)_2$  (4.40 mg, 0.020 mmol), 1,4-dioxane (0.2 ml), and the corresponding aryl halide (0.5 mmol). The reaction tube was closed with a microwave cap and irradiated with 15W of microwave energy for 20 minutes at 100 °C. After the completion of the reaction, the content of the flask was dissolved in acetone, filtered and the solvent evaporated to dryness to afford a black residue which was purified through silica gel chromatography using hexane: ethyl acetate (9:1). Following general method C, 4-bromonitrobenzene (0.10 g, 0.50 mmol) was reacted with compound **91** to afford the title compound as clear-yellow oily product (81%).  $^1H$  NMR(400 MHz,  $CDCl_3$ ): $\delta$ ppm 0.95 (t,  $J = 7.5$  Hz, H-6', 3H), 1.34-1.56 (m, H-4',5', 4H), 2.25-2.31 (m, H-3', 2H), 6.44-6.47 (m, H-1',H-2', 2H), 7.46 (d,  $J = 8.9$  Hz, H-3,5, 2H), 8.16 (d,  $J = 9.0$  Hz, H-2, 6, 2H).  $^{13}C$  NMR (100 MHz,  $CDCl_3$ ): $\delta$  ppm 13.8 (C-6'), 22.2 (C-5'), 31.1 (C-4'), 32.8 (C-3'), 123.9 (C-2,6), 126.3 (C-3,5), 128.0 (C-2'), 136.6 (C-1'), 144.4 (C-4), 146.4 (C-1). IR (neat) 2957, 2928, 1595, 1512, 1337, 1108  $cm^{-1}$ . HRMS found  $[M^+ + Na^+]$  228.0999, calculated for  $C_{12}H_{15}NO_2Na$  is 228.1000.

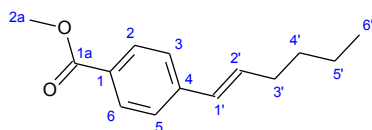
### 5.2.9 Synthesis of 4-(1*E*-hexenyl)-phenol (**96**)



Following general method C, the title compound was successfully synthesised from 4-bromophenol (0.086 g, 0.50 mmol) and compound **96** in 67% as a colourless oil.  $^1H$  NMR(400 MHz,  $CDCl_3$ ): $\delta$ ppm 0.93 (t,  $J = 7.0$  Hz, H-6', 3H), 1.36-1.50 (m, H-4',5', 4H), 2.16-2.23 (m, H-3', 2H), 6.08 (dt,  $J = 15.8$  Hz, H-2', 1H), 6.30 (d,  $J = 15.8$  Hz,

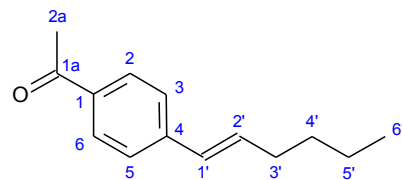
H-1', 1H), 6.77 (d,  $J = 8.6$  Hz, H-3,5, 2H), 7.23 (d,  $J = 8.5$  Hz, H-2,6, 2H).  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ ): $\delta$ ppm 13.9 (C-6'), 22.2 (C-5'), 31.2 (C-4'), 32.6 (C-3'), 67.0 (C-2'), 115.4 (C-1'), 127.1 (C-1)), 129.0 (C-2,6), 129.0 (C-3,5), 154.5 (C-4). IR (neat) 3313, 2956, 2928, 1600, 1511, 1218  $\text{cm}^{-1}$ . HRMS found  $[\text{M}^+]$  175.1125, calculated for  $\text{C}_{12}\text{H}_{15}\text{O}$  is 175.1123.

### 5.2.10 Synthesis of 4-(1*E*-hexenyl)-methyl benzoate (98)



Following general procedure C, 4-bromomethylbenzoate (0.11 g, 0.50 mmol) was reacted with compound **2.5** to afford the title compound as colourless oil (67%).  $^1\text{H}$  NMR(400 MHz,  $\text{CDCl}_3$ ): $\delta$ ppm 0.95 (t,  $J = 7.2$  Hz, H-6', 2H), 1.35-1.44 (m, H-5', 2H), 1.44-1.55 (m, H-4', 2H), 2.25 (q,  $J = 6.6$  Hz, H-3', 2H), 3.92 (s, H-2a, 3H), 6.32-6.48 (m, H-1',2', 2H), 7.40 (d,  $J = 8.1$  Hz, H-3,5, 2H), 7.97 (d,  $J = 8.0$  Hz, 2H).  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ ): $\delta$  ppm 13.8 (C-6'), 22.2 (C-5'), 31.3 (C-4'), 32.8 (C-3'), 51.9 (C-2a), 125.9 (C-4'), 129.0 (C-3,5), 129.8 (C-2,6), 134.2 (C-4), 142.5 (C-1), 167.0 (C-1a). IR (neat) 2954, 2927, 1718, 1272, 1107  $\text{cm}^{-1}$ . HRMS found  $[\text{M}^+ + \text{Na}^+]$  241.1204, calculated for  $\text{C}_{14}\text{H}_{18}\text{O}_2\text{Na}$  is 241.1204.

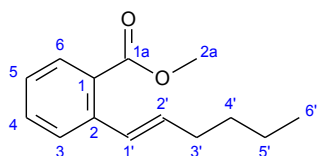
### 5.2.11 Synthesis of 4-(1*E*-hexenyl)-acetophenone (100)



Following general procedure C, 4-bromoacetophenone (0.10 g, 0.50 mmol) was reacted with compound **2.5** furnishing the title compound as colourless oil (67%).  $^1\text{H}$  NMR(400 MHz,  $\text{CDCl}_3$ ): $\delta$ ppm 0.95 (t,  $J = 7.3$  Hz, H-6', 3H), 1.33-1.43 (m, H-5', 2H), 1.43-1.56 (m, H-4', 2H), 2.21-2.29 (m, H-3', 2H), 2.58 (s, H-2a, 3H), 6.42-6.49

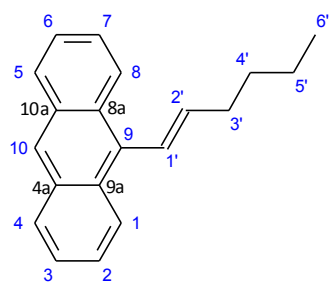
(m, H-1',2', 2H), 7.41 (d,  $J = 8.3$  Hz, H-3,5, 2H), 7.89 (d,  $J = 8.5$  Hz, H-2,6, 2H).  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ ): $\delta$ ppm 13.9 (C-6'), 22.2 (C-5'), 31.2 (C-2a), 32.8 (C-4'), 125.8 (C-3,5), 128.7 (C-2,6), 128.9 (C-2') 134.4 (C-1'), 135.4 (C-4), 142.6 (C-1), 197.4 (C-1a). MS (EI): $m/z$  (%) 103 (8), 115 (25), 131 (80), 146 (39), 159 (10), 187 (100), 202 (60) [ $\text{M}^+$ ], 202 (10). IR (neat) 2957, 2927, 1678, 1601, 1265  $\text{cm}^{-1}$ . HRMS found [ $\text{M}^+ + \text{Na}^+$ ] 225.1255, calculated for  $\text{C}_{14}\text{H}_{18}\text{ONa}$  is 225.1255.

### 5.2.12 Synthesis of 2-(1*E*-hexenyl)-methylbenzoate (102)



Following general procedure C, 2-iodomethylbenzoate (0.13 g, 0.50 mmol) was reacted with compound **2.4** to afford the title compound as colourless oil in 74% yield.  $^1\text{H}$  NMR(400 MHz,  $\text{CDCl}_3$ ): $\delta$ ppm 0.95 (t,  $J = 7.2$  Hz, H-6', 3H), 1.35-1.55 (m, H-4',5', 4H), 2.24-2.31 (m, H-3', 2H), 3.91 (s, H-2a, 3H), 6.15 (dt,  $J = 15.6$  Hz, H-2', 1H), 7.15 (m, H-1', 1H), 7.26 (dd,  $J = 7.6, 1.5$  Hz, H-3, 1H), 7.41-7.47 (m, H-4, 1H), 7.55 (dd,  $J = 7.2, 0.84$  Hz, H-5, 1H), 7.87 (dd,  $J = 7.9, 1.4$  Hz, H-6).  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ ): $\delta$  ppm 13.9, 22.2, 31.4, 32.8, 51.9, 126.4, 127.1, 128.1, 128.4, 130.2, 131.8, 134.0, 139.7, 168.0. MS (EI)  $m/z$  (%) 91 (14), 115 (24), 144 (100), 161 (69), 162 (12), 186 (7), 218 (38) [ $\text{M}^+$ ], 219 (22). IR (neat) 2954, 2927, 1720, 1247, 1076  $\text{cm}^{-1}$ . HRMS [ $\text{M}^+ + \text{Na}^+$ ] found 241.1205, calculated for  $\text{C}_{14}\text{H}_{18}\text{O}_2\text{Na}$  is 241.1204

### 5.2.13 Synthesis of 9-(1*E*-hexenyl)-anthracene (104)

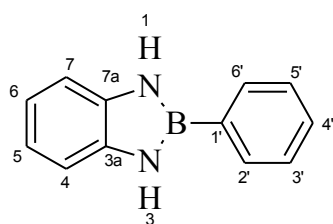


Following general procedure C, 9-bromoanthracene (0.13 g, 0.50 mmol) was reacted with compound **104** to afford the titled compound as light yellow amorphous solid,

which when recrystallised from hexane, afforded the desired product as light yellow needle-like crystals (79%), mp 53-54 °C. <sup>1</sup>H NMR(400 MHz, CDCl<sub>3</sub>):δppm 1.06 (m, H-6', 3H), 1.52-1.62 (m, H-5', 2H), 1.64-1.75 (m, H-4', 2H), 2.50-2.58 (m, H-3', 2H), 6.08 (dt, *J* = 16.1, 6.7 Hz, H-2, 1H), 7.14 (dt, *J* = 16.0, 6.7 Hz, H-1', 1H), 7.46-7.51 (m, H-2, 3, 6, 7, 4H), 7.99-8.05 (m, H-1,5, 2H), 8.32-8.39 (m, H4,8,9, 3H). <sup>13</sup>C NMR (100 MHz, CDCl<sub>3</sub>):δ ppm 14.1, 22.5, 31.6, 33.4, 125.0, 125.3, 125.7, 126.2, 128.1, 128.5, 129.6, 131.5, 133.7, 139.6. MS (EI): *m/z* (%) 189 (6), 201 (10), 202 (66), 217 (100), 218 (71), 231 (63), 260 (79) [M<sup>+</sup>], 261 (20). HRMS found 260.1565, calculated for C<sub>20</sub>H<sub>20</sub> is 260.1570.

## 5.3 EXPERIMENTAL FOR CHAPTER THREE

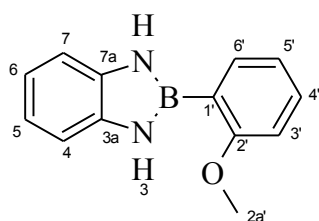
### 5.3.1 Synthesis of 2-phenylbenzo-1,3,2-diazaborole (173). General procedure D.



Arylboronic acid (1.0 equiv.) and *o*-phenylenediamine (1.0 equiv.) were dissolved in toluene (80ml) in a two neck flask equipped with a Dean and Stark Apparatus, magnetic stirrer bar and reflux condenser. This mixture was heated under reflux overnight and the solvent was removed *in vacuo*, to afford the corresponding 2-arylbenzo-1,3,2-diazaborole as a solid residue. The desired products were purified through flash column and radial chromatography using Hexane: Ethyl acetate (8:2) as an eluting solvent. The title compound was prepared according to General procedure D, using phenylboronic acid (1.00 g, 8.20 mmol) and *o*-phenylenediamine (0.89 g, 8.20 mmol) to afford 2-phenyl-1,3,2-diazaborolane **173** as a cream white crystalline product (93%). Recrystallisation of the solid residue from toluene afforded 2-phenylbenzo-1,3,2-diazaborolane **173** as a colourless round lumps mp 213-216 °C

(lit)<sup>h</sup> 212-214 °C. <sup>1</sup>H NMR (400MHz, Acetone-d<sub>6</sub>) δ<sub>H</sub>, ppm: 6.80 (s, H-1,3, 2H), 6.95-7.02 (m, H-5,6, 2H), 7.11-7.20 (m, H-4,7, 2H) 7.40-7.51 (m, H-3',4',5', 3H), 7.71-7.85 (m, H-2'6',2H). <sup>13</sup>C NMR (100 MHz, Acetone-d<sub>6</sub>) δ<sub>C</sub>, ppm: 110.9 (C-4,7), 118.6 (C-5,6), 127.9 (C-3',5'), 129.3 (C-4'), 133.3 (C-2',6'), 137.3 (C-3a,7a). <sup>11</sup>B NMR (128MHz, Acetone-d<sub>6</sub>) δ<sub>B</sub>, ppm : 28.9 { br s, CB(NH)<sub>2</sub>}. ν<sub>max</sub> (neat) 3441, 3418, 1422 cm<sup>-1</sup>. HRMS found [M<sup>+</sup>-H] = 193.0938, calculated for C<sub>12</sub>H<sub>11</sub>BN<sub>2</sub> is 194.0401.

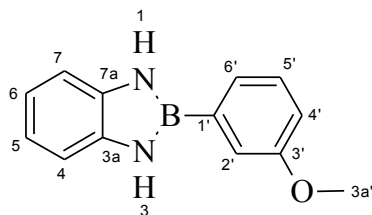
### 5.3.2 Synthesis of 2-(2-methoxyphenyl)-benzo-1,3,2-diazaborole (179)



Following general procedure D, 2-methoxyphenyl boronic acid (1.00 g, 5.18 mmol) was reacted with *o*-phenylenediamine (0.56 g, 5.18 mmol) to afford the title compound as cream white crystals (84%), mp:118-120 °C. <sup>1</sup>H NMR (400MHz, Acetone-d<sub>6</sub>) δ<sub>H</sub>, ppm: 3.98 (s, H-2a, 3H), 6.88-7.01 (m, H-4,7, 2H), 7.06-7.12 (m, H-3',5', 2H), 7.15-7.22 (m, H-5,6, 2H), 7.44-7.50 (m, H-4', 1H), 7.70 (dd, *J* = 7.3, 1.4 Hz, H-6', 1H). <sup>13</sup>C NMR (100 MHz, Acetone-d<sub>6</sub>) δ<sub>C</sub>, ppm: 55.3 (C-2a), 110.3 (C-3'), 110.9 (C-5,6), 119.0 (C-1'), 120.6 (C-4,7), 131.2 (C-5'), 134.8 (C-6'), 136.2 (C-3a, 7a), 163.6 (C-2'). IR (neat) 3467, 3423, 1434, 1418 cm<sup>-1</sup>. HRMS: found [M<sup>+</sup>-H] 223.1043, calculated for C<sub>13</sub>H<sub>13</sub>BN<sub>2</sub>O [M<sup>+</sup>] is 224.0661.

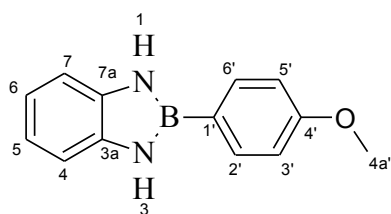
<sup>h</sup> Soloway, A. H. *J. Am. Chem. Soc.* **1959**, 82, 2442.

### 5.3.3 Synthesis of 2-(3-methoxyphenyl)benzo-1,3,2-diazaborole



Following the general procedure D, 3-methoxyphenyl boronic acid (1.00 g, 5.18 mmol) was reacted with *o*-phenylenediamine (0.56 g, 5.18 mmol) to afford the title compound (89%) as an orange-red powder. 202-204 °C  $^1\text{H}$  NMR (400MHz, Acetone- $\text{d}_6$ )  $\delta_{\text{H}}$ , ppm: 3.85 (s, H-3a, 3H), 6.86-6.90 (m, H-4,7, 2H), 6.98 (dd,  $J$  = 8.1, 2.5 Hz, H-4', 1H), 7.05-7.23 (m, H-5,6, 2H), 7.34 (t,  $J$  = 7.8 Hz, H-5', 1H), 7.48-7.54 (m, H-2',6', 2H), 8.44 (s, H-1,3, 2H).  $^{13}\text{C}$  NMR (100 MHz, Acetone- $\text{d}_6$ )  $\delta_{\text{C}}$ , ppm: 54.5 (C-OCH<sub>3</sub>), 110.9 (C-4, 7), 115.0 (C-2'), 118.3 (C-5'), 118.6 (C-5, 6), 125.5 (C-4'), 129.0 (C-6'), 137.2 (3a, 7a), 159.5 (C-3'). HRMS: found  $[\text{M}^+ - \text{H}]$  223.1043, calculated for  $\text{C}_{13}\text{H}_{13}\text{BN}_2\text{O}$   $[\text{M}^+]$  : 224.0661. IR (neat) 3414, 1425, 1410  $\text{cm}^{-1}$ .

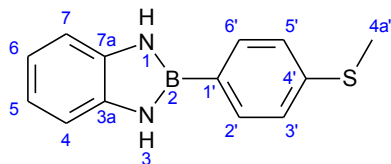
### 5.3.4 Synthesis of 2-(4-methoxyphenyl)benzo-1,3,2-diazaborole (180)



Following general procedure D, 4-methoxyphenyl boronic acid (1.00 g, 5.18 mmol) was reacted with *o*-phenylenediamine (0.56 g, 5.18 mmol) to afford the title compound as a yellowish-plate like product (78%). 243-242 °C  $^1\text{H}$  NMR (400MHz, Acetone- $\text{d}_6$ )  $\delta_{\text{H}}$ , ppm: 3.84 (s, H-4a, 2H), 6.80-6.87 (m, H-4,7, 2H), 6.98 (d,  $J$  = 8.5Hz, H-3',5', 2H), 7.08-7.12 (m, H-5,6, 2H), 7.86 (d,  $J$  = 8.7 Hz, H-2',6', 2H), 8.29 (s, H-1,3, 2H).  $^{13}\text{C}$  NMR (100 MHz, Acetone- $\text{d}_6$ )  $\delta_{\text{C}}$ , ppm: 54.4 (C-4a), 110.7 (C-3', 5'), 113.5 (C-5,6), 118.4 (C-4,7), 134.8 (C-2',6'), 137.4 (C-3a,7a), 161.0 (C-4'). HRMS: found  $[\text{M}^+ - \text{H}]$  = 223.1043, calculated for  $\text{C}_{13}\text{H}_{13}\text{BN}_2\text{O}$   $[\text{M}^+]$  is 224.0661. IR (neat) 3450, 3432, 1407  $\text{cm}^{-1}$ .

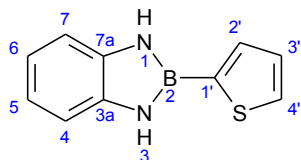


### 5.3.5 Synthesis of 2-(4-methylthiophenyl)-benzo-1,3,2-diazaborole (181).



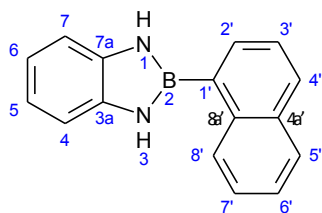
Following general procedure D, 4-methylthiophenylboronic acid (1.00 g, 5.95 mmol) was reacted with *o*-phenylenediamine (0.644 g, 5.95 mmol) to afford the title compound as a light brown solid (86%). 210-212 °C  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{H}}$ , ppm: 2.53 (s, H-4a, 3H), 6.83-6.88 (m, H-4,7, 2H), 7.07-7.13 (m, H-5,6, 2H), 7.32 (d,  $J = 8.3$  Hz, H-3,5, 2H), 7.86 (d,  $J = 8.41$  Hz, H-2,6, 2H), 8.41 (s, H-1,3, 2H).  $^{13}\text{C}\{^1\text{H}\}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{C}}$ , ppm: 14.1 (C-4a), 110.8 (C-5,6), 118.6 (C-4,7), 125.4 (C-3',5'), 133.7 (C-2',6'), 137.3 (C-3a,7a), 140.3 (C-4a'). HRMS: found  $[\text{M}^+]$  239.0816, calculated for  $\text{C}_{13}\text{H}_{13}\text{BN}_2\text{S}$  is 239.0814. IR (neat): 3447, 3432, 1583, 1393, 1352, 816, 734  $\text{cm}^{-1}$ .

### 5.3.6 Synthesis of 2-(2-thienyl)-benzo-1,3,2-diazaborole (182)



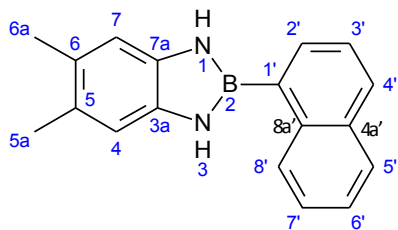
Following general procedure D, 2-thiopheneboronic acid (0.40 g, 3.13 mmol), was reacted with *o*-phenylenediamine (1.35 g, 1.25 mmol) to afford the title compound as colourless crystals (91%). 251-252 °C  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{H}}$ , ppm: 6.73 (s, H-1,3, 2H), 6.97-7.03 (m, H-4,7, 2H), 7.10-7.16 (m, H-5,6, 2H), 7.25-7.29 (m, H-3', 1H), 7.54-7.56 (m, H-4', 1H), 7.62-7.64 (m, H-2', 1H).  $^{13}\text{C}\{^1\text{H}\}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{C}}$ , ppm: 111.9 (C-5,6), 119.5 (C-4,7), 128.5 (C-3'), 130.14 (C-2'), 133.6 (C-4'), 136.0 (C-3a,7a).

### 5.3.7 Synthesis of 2-(1-naphthyl)-benzo-1,3,2-diazaborole (183)



Following general procedure D, 1-naphthylboronic acid (0.50 g, 2.19 mmol) was reacted with *o*-phenylenediamine (0.31 g, 2.19 mmol) to afford the title compound as cream white powder (81%). 186-189 °C.  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{H}}$ , ppm: 6.72 (s, H-1,3, 2H), 6.97-7.03 (m, H-4,7, 2H), 7.10-7.16 (m, H-5,6, 2H), 7.50-7.56 (m, H-3',6',7, 3H), 7.79 (dd,  $J = 6.76, 1.01$  Hz, H-8', 1H), 7.88-7.96 (m, H-4',5', 2H), 8.25-8.31 (m, H-2', 1H).  $^{13}\text{C}\{^1\text{H}\}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{C}}$ , ppm: 19.8, 112.3, 125.2, 125.6, 126.1, 127.3, 128.2, 128.6, 129.2, 132.6, 133.3, 134.3, 136.1.  $^{11}\text{B}$  NMR (128 MHz,  $\text{DCCl}_3$ )  $\delta$ : 29.10 (s). HRMS found 243.1099, calculated for  $\text{C}_{16}\text{H}_{12}\text{BN}_2$  is 243.1094. IR (neat): 3454, 3451, 2925, 2854, 1461, 1431, 1420, 1379, 1341, 1330, 1285, 1263, 1233, 1166, 995, 857, 801, 778  $\text{cm}^{-1}$ .

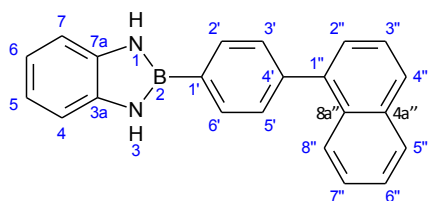
### 5.3.8 Synthesis of 2-(1-naphthyl)-4,5-dimethyl-benzo-1,3,2-diazaborole (189)



4,5-Dimethyl-*o*-phenylenediamine (0.10 g, 0.73 mmol), 1-naphthyl boronic acid (0.19 g, 1.10 mmol) and toluene (8 ml) were placed into a 100 ml round bottom flask and heated to reflux until all the solvent has evaporated. The resulting brown solid was purified by column chromatography using hexane: ethyl acetate (9:1) as an eluting solvent to afford the title compound as cream white powder (79%). mp 189-202 °C  $^1\text{H}$

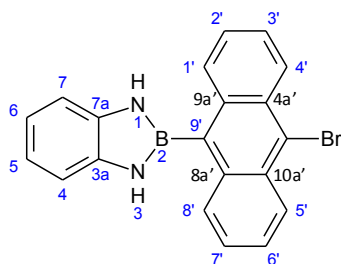
NMR (400 MHz, CDCl<sub>3</sub>)  $\delta_{\text{H}}$ , ppm: 2.35 (s, H-5a,6a, 6H), 6.72 (s, H-1,3, 2H), 6.99 (s, H-4,7, 2H), 7.50-7.56 (m, H-3'6'7', 3H), 7.79 (dd,  $J$  = 6.7, 1.0 Hz, H-8',1H), 7.88-7.96 (m,4'5', 2H), 8.25-8.31 (m, H-2', 1H). <sup>13</sup>C{<sup>1</sup>H} NMR (100 MHz, CDCl<sub>3</sub>)  $\delta_{\text{C}}$ , ppm: 19.8, 112.3, 125.2, 125.6, 126.1, 127.3, 128.2, 128.6, 129.2, 132.6, 133.3, 134.3, 136.1. <sup>11</sup>B NMR (128 MHz, DCCl<sub>3</sub>,)  $\delta$ : 29.10 (s). HRMS found 271.1411, calculated for C<sub>18</sub>H<sub>17</sub>BN<sub>2</sub> is 271.1407. IR (neat): 3454, 3451, 2925, 2854, 1461, 1431, 1420, 1379, 1341, 1330, 1285, 1263, 1233, 1166, 995, 857, 801, 778 cm<sup>-1</sup>.

### 5.3.9 Synthesis of 2-(1-naphthyl)-phenylbenzo-1,3,2-diazaborole (190)



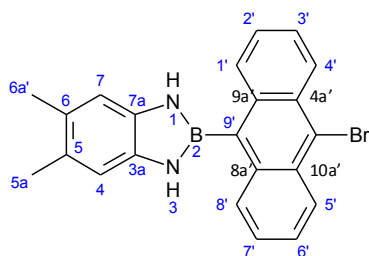
A mixture of 4-(1-naphthyl)-phenylboronic acid (0.13 g, 0.51 mmol), *o*-phenylenediamine (0.055 g, 0.51 mmol), toluene (5 ml) was heated to reflux in an open air until all the solvent has evaporated. The resulting light brown solid was purified by silica gel column chromatography with hexane: ethyl acetate (8:2) as eluent affording the title compounds as a white powder (64%).mp 250-252 °C <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>)  $\delta_{\text{H}}$ , ppm: 6.88 (s, H-1,3, 2H), 6.97-7.06 (m, H-4,7, 2H), 7.12-7.21 (m, H-5,6, 2H), 7.42-7.58 (m,H-2'',3'',6'',7'', 4H), 7.60 (d,  $J$  = 8.0 Hz, H-3',5', 2H), 7.73-7.79 (m, H-8'', 1H), 7.88 (d,  $J$  = 8.0 Hz, H-2',6', 2H), 7.91-8.02 (m, H-4'',5'',2H). <sup>13</sup>C{<sup>1</sup>H} NMR (100 MHz, CDCl<sub>3</sub>)  $\delta_{\text{C}}$ , ppm: 111.0, 111.3, 125.3, 125.5, 125.7, 126.0, 126.8, 127.0, 127.7, 127.9, 128.2, 128.4, 129.8, 130.0, 131.5, 132.8, 133.0, 133.8, 136.3, 140.0, 142.2. HRMS: found [ $\text{M}^+$ ] 320.1496, calculated for C<sub>22</sub>H<sub>17</sub>BN<sub>2</sub> is 320.1485. IR (neat): 3439, 3048, 1610, 1438, 1431, 1393, 1352, 1270, 1248, 838, 797, 771, 737, 696 cm<sup>-1</sup>.

### 5.3.10 Synthesis of 2-(10-bromo-9-anthryl)benzo-1,3,2-diazaborole (172)



A 50 ml round-bottomed flask containing a magnetic stirrer bar was charged with 10-bromoanthracene-9-boronic acid (0.20 g, 0.67 mmol), o-phenylenediamine (0.14 g, 1.33 mmol) and toluene (10 ml). The reaction mixture was heated under reflux until all the solvent has evaporated. The residue was dissolved in acetone and purified by column chromatography using hexane: ethyl acetate (9:1) to provide the titled compound as a yellow powder (92%).  $^1\text{H}$  NMR (400 MHz, acetone- $d_6$ )  $\delta_{\text{H}}$ , ppm: 6.98–7.05 (m, H-4,7, 2H), 7.27–7.32 (m, H-5,6, 2H), 7.49–7.56 (m, H-3',6', 2H), 7.66–7.72 (m, H-2',7', 2H), 8.17 (d,  $J$  = 8.6 Hz, H-4',5', 2H), 8.58 (d,  $J$  = 8.7 Hz, H-1',8', 2H).  $^{13}\text{C}$  { $^1\text{H}$ } NMR (100 MHz, acetone- $d_6$ )  $\delta_{\text{C}}$ , ppm: 111.2 (C-5,6), 119.0 (C-4,7), 123.0 (C-10'), 125.3 (C-3',6'), 127.2 (C-2',7'), 127.4 (C-1',8'), 130.0 (3a,7a), 130.2 (C-4',5'), 136.0 (C-4a,10a), 137.1 (C-8a',9a'). HRMS: found  $[\text{M}^+]$  293.1259, calculated for  $\text{C}_{20}\text{H}_{16}\text{BrN}_2$  is 293.1250. IR (neat): 3459, 3454, 3034, 2951, 2921, 2867, 2850, 2040, 1430, 1304, 1274, 1253, 1162, 743, 726, 696  $\text{cm}^{-1}$ .

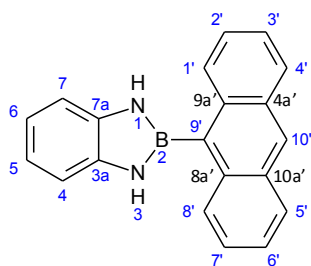
### 5.3.11 Synthesis of 2-(10-bromo-9-anthryl)-4,5-dimethylbenzo-1,3,2-diazaborole (189)



A 100 ml round bottomed-flask equipped with a stirred bar, Dean and Stark apparatus and reflux condenser was charged with 10-bromoanthracene-9-boronic acid (0.40 g,

1.34 mmol), 4,5-dimethyl-*o*-phenylenediamine (0.36 g, 2.68 mmol) and toluene (50 ml). The reaction mixture was heated to reflux with continuous withdrawal of the solvent from the side arm of Dean and Stark apparatus until all the solvent has evaporated. The remaining brown solid was cooled to room temperature and dissolved in acetone. The crude product was purified through silica gel with hexane: ethyl acetate (9:1) as eluent affording the titled compound as yellow crystalline product (86%).  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{H}}$ , ppm: 2.38 (s, H-5a,6a, 6H), 6.77 (s, H-1,3, 2H), 7.04 (s, H-4,7, 2H), 7.37-7.44 (m, H-3',6', 2H), 7.56-7.63 (m, H-2',7', 2H), 8.08 (d,  $J = 8.6$  Hz, H-4',5', 2H), 8.60 (d,  $J = 8.8$  Hz, H-1',8', 2H).  $^{13}\text{C}$   $\{^1\text{H}\}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{C}}$ , ppm: 19.8 (C-5a,6a), 112.4 (C-5,6), 124.4 (C-4,7), 125.3 (C-10'), 126.8 (C-3',5'), 127.6 (C-2',7'), 128.0 (C-1',8'), 128.0 (C-3a,7a), 130.1 (C-4',5'), 134.2 (4a', 10a'), 136.0 (C-8a',9a').

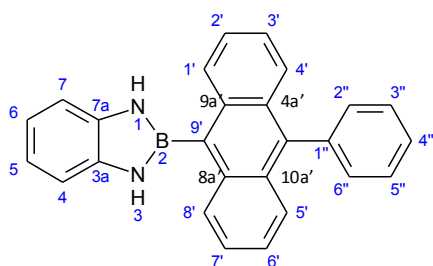
### 5.3.12 Synthesis of 2-(9-anthryl)-benzo-1,3,2-diazaborole (184)



A single-neck 100 ml round bottomed flask was charged with magnesium turnings (0.36 g, 1.5 equiv.) and dry THF (5 ml). 9-Bromoanthracene solution (0.60 g, 2.52 mmol) in dry THF (5 ml) was added dropwise to the flask containing magnesium turnings until the solvent has started refluxing. After the reaction has reached room temperature, THF (40 ml) was added and the reaction mixture was cooled to  $-78^\circ\text{C}$ . Trimethylborate solution (1.12 ml, 10.08 mmol) was added *via* a disposable syringe while the temperature is maintained at  $-78^\circ\text{C}$ . After the Addition of trimethylborate solution, the reaction mixture was allowed to reach room temperature and stirred overnight. Excess magnesium was filtered off and the solvent evaporated to dryness. To the resulting light yellow solid, was added toluene (10 ml) and *o*-phenylenediamine (0.27 g, 2.52 mmol). The mixture was heated to reflux in an open air until all the solvent has evaporated. The crude product was purified by silica gel chromatography with hexane: ethyl acetate (9:1) as eluting solvent affording the title compound as colourless plates like solid (52%).  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{H}}$ , ppm: 6.95 (br. s, 2H), 7.06-7.13 (m, H-4,7, 2H), 7.22-7.30 (m, H-5,6, 2H), 7.37-7.44 (m,

H-3',6',2H), 7.44-7.51 (m, H-2',7',2H), 8.05 (d,  $J = 8.4$  Hz, 4',5', 2H), 8.12 (d,  $J = 8.8$  Hz, H-1',8', 2H), 8.52 (s, H-10', 1H).  $^{13}\text{C}\{^1\text{H}\}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{C}}$ , ppm: 111.3 (C-5,6), 119.5 (C-4,7), 125.0 (C-10'), 125.2 (C-3'5'), 127.1 (C-2'7'), 127.9 (C-1',8'), 128.7 (C-3a,7a), 129.3 (C-4',5'), 131.1 (C-4a',10a'), 133.4 (C-8a',9a'). HRMS: found  $[\text{M}^+]$  293.1259, calculated for  $\text{C}_{20}\text{H}_{14}\text{BN}_2$  293.1250. IR (neat): 3434, 3048, 2959, 1438, 1401, 1308, 1259, 1162, 1092, 1010, 790, 734  $\text{cm}^{-1}$ .

### 5.3.13 Synthesis of 2- {9-anthryl-10-(1-phenyl)}-benzo-1,3,2-diazaborole (185).

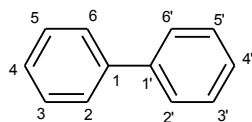


A 50 ml round bottomed-flask equipped with a magnetic stirrer bar was charged with 10-phenyl-9-anthracenyl boronic acid (0.18 g, 0.60 mmol), *o*-phenylenediamine (0.30g, 1.19 mmol) and toluene (25 ml). The mixture was heated to reflux until all the solvent has evaporated, cooled to room temperature and dissolved in acetone. The crude product was purified through silica-gel using hexane: ethyl acetate (8:2) as eluent affording the title compound as yellow powder (43%).  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{H}}$ , ppm: 6.97 (s, 2H), 7.09-7.17 (m, 2H), 7.25-7.32 (m, 2H), 7.34-7.45 (m, 4H), 7.45-7.54 (m, 2H), 7.55-7.69 (m, 3H), 7.74 (d,  $J = 8.26$  Hz, 2H), 8.17 (d,  $J = 8.38$  Hz, 2H).  $^{13}\text{C}\{^1\text{H}\}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{C}}$ , ppm: 111.3, 119.6, 124.9, 125.0, 127.3, 127.5, 128.4, 129.5, 129.7, 131.2, 135.1, 136.2, 138.4, 139.0. HRMS found 369.1558, calculated for  $\text{C}_{26}\text{H}_{19}\text{BN}_2$  is 369.4563.

## 5.4 EXPERIMENTAL FOR CHAPTER FOUR

**General procedure E:** A microwave tube equipped with a magnetic stirrer bar was charged with the corresponding 2-arylbenzo-1,3,2-diazaborole (1.0 equiv.), Pd(OAc)<sub>2</sub> (4.0 mol %) and PCy<sub>3</sub> (8.0 mol %). The tube was fitted with a rubber septum and continuously purged with argon gas for 20 minutes. In a separate 10 ml round bottomed flask, K<sub>3</sub>PO<sub>4</sub>·H<sub>2</sub>O (3.0 equiv.) was dissolved in water (0.2 ml) and aryl bromide (0.50 ml) was added. The flask was fitted with a rubber septum and argon was bubbled through the solution for 20 minutes. The contents of the round bottom flask was transferred *via* a cannula into a microwave tube which was capped and immediately irradiated in a closed vessel with 80W of microwave energy at 100 psi and 100 °C for 10 minutes. The reaction resulted in a black solid residue and an upper liquid layer. The reaction mixture was diluted with dichloromethane (5.0 ml), filtered and concentrated *in vacuo*. The resulting black residue was purified through a flash and radial chromatography using hexane: ethyl acetate (9:1) as eluting solvent.

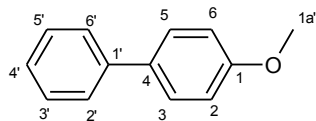
### 5.4.1 Synthesis of biphenyl (253)



Following general procedure E, 2-phenylbenzo-1,3,2-diazaborole **173** (0.15 g, 0.77 mmol) was coupled with bromobenzene **252** (0.50 ml) to afford **253** as cream white crystalline product (0.098 g, 88%): mp 69-70 °C (lit.<sup>i</sup>: 69-70 °C). <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>) δ<sub>H</sub>, ppm: 7.34-7.40 (m, 2H), 7.42-7.50 (m, 4H), 7.59-7.64 (m, 4H). <sup>13</sup>C{<sup>1</sup>H} NMR (100 MHz, CDCl<sub>3</sub>) δ<sub>C</sub>, ppm: 127.1 (C-2', 2, 6', 6), 127.2 (C-4', 4), 128.7 (C-3', 3, 5', 5). MS (EIMS): *m/z* (%) 154 [M<sup>+</sup>] (100%), 153 (41%), 152 (34%), 155 (14%), 151(11%). IR (neat): 3034, 1478, 1428, 1345, 1170, 1042, 1006 cm<sup>-1</sup>.

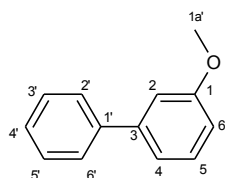
<sup>i</sup> Zhang, L.; Wang, L.; Li, H.; Li, P. *Synth. Commun.* **2008**, 38, 1498

## 5.4.2 Synthesis of 4-phenylanisole (254)



Following general procedure E, 2-phenylbenzo-1,3,2-diazaborole **173** (0.15 g, 0.77 mmol) was reacted with 4-bromoanisole **156** (0.50 ml) to afford **254** as a white powder (62%): mp 90-91°C (lit.<sup>j</sup>: 90-91°C). <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>) δ<sub>H</sub>, ppm: 3.89 (s, 3H), 7.00 (d, *J* = 8.9 Hz, 2H), 7.31-7.39 (m, 1H), 7.43 (t, *J* = 7.8 Hz, 2H), 7.55-7.64 (m, 4H). <sup>13</sup>C {<sup>1</sup>H} NMR (100 MHz, CDCl<sub>3</sub>) δ<sub>C</sub>, ppm: 55.3 (C-1a'), 114.2 (C-2, 6), 126.6 (C-4'), 126.7 (C-2; 6'), 128.1 (C-3', 5'), 128.7 (C-3, 5), 133.8 (C-4), 140.8 (C-1'), 159.2 (C-1). MS (EIMS) *m/z* (%): 184 [M<sup>+</sup>] (100%), 169 (77%), 141 (60%), 115 (32%), 185 [M<sup>+</sup> + 1] (15%). IR (neat): 3034, 3003, 2963, 2837, 1891, 1604, 1582, 1521, 1484, 1464, 1438, 1450, 1407, 1344, 1286, 1248, 1219, 1119, 1034 cm<sup>-1</sup>.

## 5.4.3 Synthesis of 3-phenylanisole (180)



Following general procedure E, 2-(3-methoxyphenyl)-benzo-1,3,2-diazaborole (0.20 g, 0.89 mmol) was reacted with bromobenzene **252** (0.50 ml) to afford **180** as a colorless oil<sup>k,l</sup> (72%): <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>) δ<sub>H</sub>, ppm: 3.90 (s, 3H), 6.93 (dd, *J* = 8.3, 2.6 Hz, 1H), 7.15-7.18 (m, 1H), 7.20-7.24 (m, 1H), 7.36-7.42 (m, 2H), 7.44-7.50 (m, 2H), 7.60-7.65 (m, 2H). <sup>13</sup>C {<sup>1</sup>H} NMR (100 MHz, CDCl<sub>3</sub>) δ<sub>C</sub>, ppm: 55.3 (C-1a'), 112.7 (C-6), 112.9 (C-2), 119.7 (C-4), 127.2 (C-3', 5'), 127.4 (C-4'), 128.7 (C-2', 6'), 129.7 (C-5), 141.1 (C-1'), 142.8 (C-3), 159.9 (C-1). MS (EIMS) *m/z* (%): 184 [M<sup>+</sup>] (100%), 154 (38%), 115 (24%), 155 (24%), 115 (23%), 153 (21%), 141

<sup>j</sup> Desmarests, C.; Omar-Amrani, R.; Walcarius, A.; Lambert, J.; Champagne, B.; Fort, Y.; Schneider, R. *Tetrahedron* **2008**, *64*, 372.

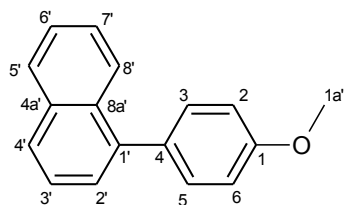
<sup>k</sup> Bolliger, J. L.; Fresh, C. M. *Chem-Eur. J.* **2010**, *16*, 4075.

<sup>l</sup> Wei, C.; Pinhua, L.; Lui, W. *Tetrahedron* **2011**, *67*, 318.



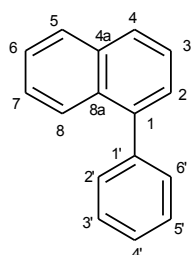
(16%), 185 [ $M^+ + 1$ ] (15%). IR (neat): 2934, 1558, 1464, 1418, 1356, 1585, 1238, 1182, 1136, 1013  $\text{cm}^{-1}$ .

#### 5.4.4 Synthesis of 1-(4-methoxyphenyl)-naphthalene (256)



Following general procedure E, 2-(1-naphthyl)-benzo-1,3,2-diazaborole (**183**) (0.20 g, 0.82 mmol) was reacted with 4-bromoanisole **156** (0.50 ml) to afford **256** as colourless crystals (68%): mp 116-117 °C (lit.<sup>m</sup>: 116-117 °C).  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{H}}$ , ppm: 3.92 (s, 3H), 7.05 (d,  $J = 8.7$  Hz, 2H), 7.40-7.47 (m, 4H), 7.47-7.55 (m, 2H), 7.85 (d,  $J = 8.3$  Hz, 1H), 7.93 (t,  $J = 9.1$  Hz, 2H).  $^{13}\text{C}\{^1\text{H}\}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{C}}$ , ppm: 55.36 (C-1a'), 113.7 (C-2, 6), 125.4 (C-2'), 125.7 (C-6'), 125.9 (C-7') 126.0 (C-5'), 12.9 (C-4'), 127.3 (C-8'), 128.2 (C-3') 131.1 (C-3, 5), 131.8 (C-4a'), 133.1 (C-8a'), 133.8 (C-4), 139.9 (C-1'), 158.9 (C-1). MS (EIMS)  $m/z$  (%): IR (neat): 2922, 2852, 1895, 1737, 1607, 1505, 1462, 1438, 1393, 1282, 1240, 1174, 1106, 1030  $\text{cm}^{-1}$ .

#### 5.4.5 Synthesis of 1-(phenyl)-naphthalene (257)



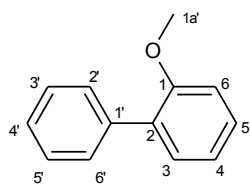
Following general procedure E, 2-(1-naphthyl)benzo-1,3,2-diazaborole (0.10 g, 0.50 mmol) was reacted with bromobenzene **252** (0.5 ml) to afford **257** as a colourless oil<sup>n</sup>

<sup>m</sup> Wang, L.; Lu, W. *Org. Lett.* **2009**, *11*, 1079.

<sup>n</sup> Nandurkar, N. S.; Bhanage, B. M. *Tetrahedron* **2008**, *64*, 3655.

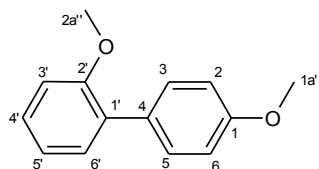
(85%).  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{H}}$ , ppm: 7.43-7.48 (m, 3H), 7.48-7.57 (m, 6H), 7.89 (d,  $J = 8.2$  Hz, 1H), 7.90-7.96 (m, 2H).  $^{13}\text{C}\{^1\text{H}\}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{C}}$ , ppm: 125.3 (C-2), 125.7 (C-4'), 126.0 (C-5), 126.0 (C-4), 126.9 (C-6), 127.2 (C-7), 127.6 (C-8), 128.2 (C-2', 6'), 130.0 (C-3, 3', 5'), 131.6 (C-4a), 133.8 (C-8a), 140.2 (C-1), 140.7 (C-1'). MS (EIMS)  $m/z$  (%): 101 (6), 200 (9), 202 (45), 204 [ $\text{M}^+$ ] (100), 205 [ $\text{M}^+ + 1$ ]. IR (neat): 1596, 1494, 1442, 1431, 1356, 1285, 1186, 1182, 1136, 1125, 1112, 1054, 1028  $\text{cm}^{-1}$ .

#### 5.4.6 Synthesis of 2-phenylanisole (258)



Following general procedure E, 2-(2-methoxyphenyl)benzo-1,3,2-diazaborole (0.20 g, 0.89 mmol) was reacted with bromobenzene **178** (0.50 ml) to afford **258** as a light yellow oil<sup>9,10</sup> (68%):  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{H}}$ , ppm: 3.85 (s, 3H), 7.01-7.10 (m, 2H), 7.33-7.39 (m, 3H), 7.42-7.48 (m, 2H), 7.55-7.60 (m, 2H).  $^{13}\text{C}\{^1\text{H}\}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{C}}$ , ppm: 55.5 (C-1a'), 111.3 (C-6), 120.8 (C-4), 126.9 (C-4'), 127.9 (C-2', 6'), 128.6 (C-5), 129.55 (C-3', 5'), 130.9 (C-3), 130.9 (C-2), 138.5 (C-1'), 156.5 (C-1). MS (EIMS)  $m/z$  (%): 184 [ $\text{M}^+$ ] (100%), 141 (57%), 169 (53%), 115 (39%), 168 (14%), 185 [ $\text{M}^+ + 1$ ] (13%). IR (neat): 2956, 1557, 1514, 1485, 1456, 1402, 1360, 1238, 1125, 1054, 1028  $\text{cm}^{-1}$ .

#### 5.4.7 Synthesis of 4-(2-methoxyphenyl)-anisole (259)

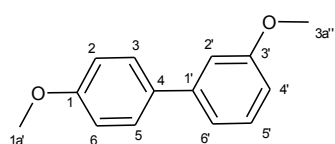


Following general procedure E, 2-(2-methoxyphenyl)benzo-1,3,2-diazaborole (0.20 g, 0.89 mmol) was reacted with 4-bromoanisole **156** (0.50 ml) to afford **259** as a white powder (65%) mp 69-70 °C (lit.<sup>o</sup>: 70-71°C) :  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{H}}$ ,

<sup>o</sup> Qin, C.; Lu, W. *J. Org. Chem.* **2008**, 73, 7424.

ppm: 3.83 (3H, s), 3.87 (s, 3H), 6.94-7.04 (m, 4H), 7.28-7.36 (m, 2H), 7.50 (d,  $J = 8.8$  Hz, 2H).  $^{13}\text{C}\{^1\text{H}\}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{C}}$ , ppm: 55.27 (C-1a'), 55.57 (C-2a'), 111.30 (C-3'), 113.5 (C-2,6), 120.8 (C-5'), 128.1 (C-4'), 130.4 (C-1'), 130.6 (C-3, 5), 130.7 (C-6'), 130.9 (C-4), 156.5 (C-1), 158.7 (C-2'). MS (EIMS)  $m/z$  (%): 214 [ $\text{M}^+$ ] (100%), 199 (56%), 184 (44%), 128 (23%), 215 [ $\text{M}^+ + 1$ ] (15%). IR (neat): 3000, 2956, 2835, 1727, 1596, 1516, 1485, 1463, 1408, 1263, 1239, 1179, 1121, 1106, 1052, 1035, 1017, 1002  $\text{cm}^{-1}$ .

#### 5.4.8 Synthesis of 4-(3-methoxyphenyl)-anisole (**260**)



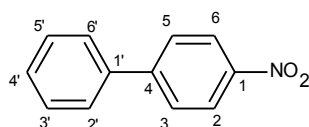
Following general procedure E, 2-(3-methoxyphenyl)benzo-1,3,2-diazaborole (0.20 g, 0.89 mmol) was reacted with 4-bromoanisole **156** (0.50 ml) to afford **260** as a white powder (76%): mp 58-59 °C (lit.<sup>P</sup>: 58-60 °C):  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{H}}$ , ppm: 3.88 (s, 3H), 3.89 (s, 3H), 6.88 (dd,  $J = 8.1, 1.7$  Hz, 1H), 7.00 (d,  $J = 8.7$  Hz, 2H), 7.10-7.13 (m, 1H), 7.17 (d,  $J = 7.8$  Hz, 1H), 7.36 (t,  $J = 8.0$  Hz, 1H), 7.55 (d,  $J = 8.7$  Hz, 2H).  $^{13}\text{C}\{^1\text{H}\}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{C}}$ , ppm: 55.2 (C-1a'), 55.3 (C-3a'), 112.0 (C-4'), 112.5 (C-2'), 114.1 (C-2, 6), 119.3 (C-6'), 128.4 (C-3, 5), 129.6 (C-5'), 133.6 (C-4), 142.3 (C-1'), 159.2 (C-1), 159.9 (C-3'). MS (EIMS)  $m/z$  (%): 214 [ $\text{M}^+$ ] (100%), 199 (56%), 184 (44%), 128 (23%), 215 [ $\text{M}^+ + 1$ ] (15%). IR (neat): 3003, 2963, 2837, 1727, 1596, 1484, 1464, 1286, 1248, 1240, 1119, 1034  $\text{cm}^{-1}$ .

**General Procedure (F):** A microwave tube equipped with a magnetic stirrer bar was charged with the corresponding 2-arylbenzo-1,3,2-diazaborole (1.5 equiv.),  $\text{Pd}(\text{OAc})_2$  (4.0 mol %),  $\text{PCy}_3$  (8.0 mol%) and aryl bromide (1.0 equiv.). The tube was fitted with a rubber septum and continuously purged with argon for 20 minutes. In a separate 10 ml round bottomed flask,  $\text{K}_3\text{PO}_4 \cdot \text{H}_2\text{O}$  (3.0 equiv.) was dissolved in water (0.2 ml) and toluene (1.0 ml) was added. The flask was fitted with a rubber septum and argon was bubbled into the solution for 20 minutes. The content of the round bottom flask was transferred *via* cannula into a microwave tube which was capped and immediately

<sup>P</sup> Itoh, Y.; Bossi, A.; Hamel, E.; Lin, C. M. *Helvetica Chimica Acta* **1988**, 71, 1199.

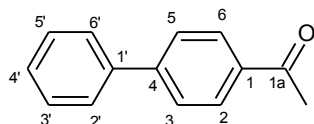
irradiated in a closed vessel with 80W of microwave energy at 100 Psi and 100 °C for 10 minutes. The content of the tube was transferred to a beaker and aqueous hydrochloric acid (2 M, 3.0 ml) was added to hydrolyze excess 2-arylbenzo-1,3,2-diazaborole. The reaction mixture was stirred at room temperature for 10 minutes and the upper black layer was extracted with acetone and concentrated in *vacuo*. The resulting black residue was purified through a short silica column followed by radial chromatography using hexane: ethyl acetate (9:1) as eluting solvent.

### 5.4.9 Synthesis of 4-phenylnitrobenzene (262)



Following general procedure F, 2-phenylbenzo-1,3,2-diazaborole (0.29 g, 1.49 mmol) was reacted with 4-bromonitrobenzene **261** (0.20 g, 0.99 mmol) to afford **262** as colourless crystals (91%) mp 112-114 °C (lit.<sup>q</sup>: 112-115° C): <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>) δ<sub>H</sub>, ppm: 7.43-7.56 (m, 3H), 7.61-7.67 (m, 2H), 7.76 (d, *J* = 8.9 Hz, 2H), 8.32 (d, *J* = 9.0 Hz, 2H). <sup>13</sup>C{<sup>1</sup>H} NMR (100 MHz, CDCl<sub>3</sub>) δ<sub>C</sub>, ppm: 124.0 (C-3', 5'), 127.3 (C-2', 6'), 127.7 (C-3, 5), 128.9 (C-4'), 129.1 (C-2, 6), 138.7 (C-1'), 147.1 (C-1), 147.6 (C-4). MS (EIMS): *m/z* (%): 115 (11), 141 (41), 152 (93), 169 (70), 199 [M<sup>+</sup>] (100), 200 [M<sup>+</sup>+1] (15). IR (neat): 3098, 3078, 1987, 1930, 1593, 1511, 1449, 1404, 1338, 1286, 1103, 1079 cm<sup>-1</sup>.

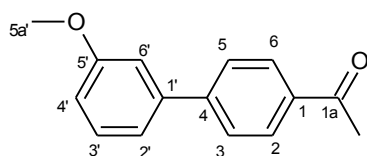
### 5.4.10 Synthesis of 4-phenylacetophenone (264)



<sup>q</sup> Milanesi, S.; Fagnoni, M.; Albini, A. *J. Org. Chem.* **2005**, *70*, 603.

Following general procedure F, 2-phenylbenzo-1,3,2-diazaborole (0.29 g, 1.52 mmol) was reacted with 4-bromoacetophenone **263** (0.20 g, 1.01 mmol) to afford **264** as colourless needle-like crystals (74%): mp 123-124 °C (lit.<sup>†</sup>: 122-124 °C): <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>) δ<sub>H</sub>, ppm: 2.66 (s, 3H), 7.38-7.44 (m, 1H), 7.44-7.52 (m, 2H), 7.65 (d, *J* = 8.2 Hz, 2H), 7.70 (d, *J* = 7.6 Hz, 2H), 8.05 (d, *J* = 7.7 Hz, 2H). <sup>13</sup>C{<sup>1</sup>H} NMR (100 MHz, CDCl<sub>3</sub>) δ<sub>C</sub>, ppm: 26.62 (C(O)CH<sub>3</sub>), 127.2 (C-2', 6'), 127.2 (C-3, 5), 128.2 (C-4'), 128.9 (C-3', 5'), 128.9 (C-2, 6), 135.9 (C-1'), 139.9 (C-4), 145.8 (C-1), 197.6 (C(O)CH<sub>3</sub>). MS (EIMS) *m/z* (%): 181 (100%), 152 (54%), 153 (47%), 196 [M<sup>+</sup>] (41%), 151 (16%), 197 [M<sup>+</sup> + 1] (9%), 154 (6%). IR (neat): 2921, 2853, 1677, 1600, 1559, 1485, 1451, 1423, 1403, 1358, 1282, 1260, 1178, 1121, 1077, 1019 cm<sup>-1</sup>.

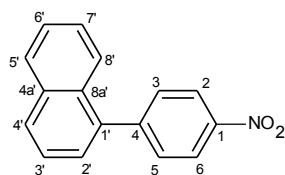
#### 5.4.11 Synthesis of 4-(3-methoxyphenyl)-acetophenone (**265**)



Following general procedure F, 2-(3-methoxyphenyl)benzo-1,3,2-diazaborole (0.30 g, 1.34 mmol) was reacted with 4-bromoacetophenone **263** (0.18 g, 0.89 mmol) to afford **265** as a cream white powder (83%): mp 88-90 °C (lit.<sup>3</sup>: 61-63 °C). <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>) δ<sub>H</sub>, ppm: 2.66 (s, 3H), 3.90 (s, 3H), 6.96 (dd, *J* = 8.4, 2.1 Hz, 1H), 7.17 (s, 1H), 7.23 (d, *J* = 7.6 Hz, 1H), 7.40 (t, *J* = 7.9 Hz, 1H), 7.69 (d, *J* = 8.3 Hz, 2H), 8.04 (d, *J* = 8.2 Hz, 2H). <sup>13</sup>C {<sup>1</sup>H} NMR (100 MHz, CDCl<sub>3</sub>) δ<sub>C</sub>, ppm: 26.61 (C(O)CH<sub>3</sub>), 55.36 (OCH<sub>3</sub>), 113.1 (C-4'), 113.5 (C-2'), 119.7 (C-6'), 127.2 (C-2, 6), 128.8 (C-3, 5), 129.9 (C-5'), 141.4 (C-4), 145.6 (C-1'), 160.0 (C-3'), 197.6 (C(O)CH<sub>3</sub>). MS (EIMS) *m/z* (%): 211 (100%), 226 [M<sup>+</sup>] (53%), 168 (19%), 153 (19%), 139 (15%), 227 [M<sup>+</sup> + 1] (8%). IR (neat): 2934, 2837, 1673, 1591, 1538, 1485, 1464, 1398, 1270, 1217, 1179, 1116, 1029 cm<sup>-1</sup>.

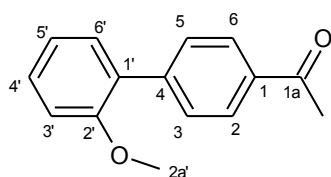
<sup>†</sup> Metallinos, C.; Barrett, F. B.; Chaytor, J. L.; Heska, M. E. A. *Org. Lett.* **2004**, 6, 3641.

### 5.4.12 Synthesis of 1-(4-nitrophenyl)-naphthalene (267)



Following general procedure F, 2-(1-naphthyl)benzo-1,3,2-diazaborole (0.30 g, 1.23 mmol) was reacted with 4-bromonitrobenzene **261** (0.17 g, 0.82 mmol) to afford **267** as colourless crystals (96%): mp 132-133 °C (lit.<sup>7</sup>:132-133 °C). <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>) δ<sub>H</sub>, ppm: 7.40-7.52 (m, 4H), 7.52-7.62 (m, 2H), 7.69 (d, *J* = 8.8 Hz, 2H), 7.80 (d, *J* = 8.4 Hz, 1H), 7.96 (dd, *J* = 7.8, 2.9 Hz, 2H), 8.38 (d, *J* = 8.8 Hz, 2H). <sup>13</sup>C{<sup>1</sup>H} NMR (100 MHz, CDCl<sub>3</sub>) δ<sub>C</sub>, ppm: 123.5 (C-3, 5), 125.1 (C-2'), 125.3 (C-7'), 126.2 (C-6'), 126.73 (C-5'), 127.0 (C-4'), 128.5 (C-8'), 128.9 (C-3'), 130.9 (C-2, 6), 130.9 (C-4a'), 133.8 (C-8a'), 137.8 (C-1'), 147.2 (C-1), 147.6 (C-4). MS (EIMS) *m/z* (%): 202 (100%), 249 [M<sup>+</sup>] (95%), 203 (59%), 203 (41%), 200 (14%), 201 (19%), 219 (16%), 250 [M<sup>+</sup> + 1] (13%). IR (neat): 2929, 1937, 1723, 1596, 1513, 1395, 1346, 1311, 1285, 1250, 1106, 1015 cm<sup>-1</sup>.

### 5.4.13 Synthesis of 4-(2-methoxyphenyl)-acetophenone (268)

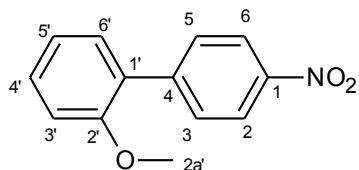


Following general procedure F, 2-(2-methoxyphenyl)benzo-1,3,2-diazaborole (0.30 g, 1.34 mmol) was reacted with 4-bromoacetophenone **263** (0.18 g, 0.89 mmol) to afford **268** as a white powder (90%): mp 105-107 °C (lit.<sup>8</sup>: 106-107 °C). <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>) δ<sub>H</sub>, ppm: 2.66 (s, 3H), 3.84 (s, 3H), 7.02-7.09 (m, 2H), 7.33-7.41 (m, 2H), 7.65 (d, *J* = 8.6 Hz, 2H), 8.02 (d, *J* = 8.4 Hz, 2H). <sup>13</sup>C{<sup>1</sup>H} NMR (100 MHz, CDCl<sub>3</sub>) δ<sub>C</sub>, ppm: 26.5 (C(O)CH<sub>3</sub>), 55.5 (OCH<sub>3</sub>), 111.4 (C-3'), 120.9 (C-5'), 128.06

<sup>8</sup> Quasdorf, W. K.; Riecher, M.; Petrova, V. K. Garg, K. N. *J. Am. Chem. Soc.* **2009**, *131*, 17748.

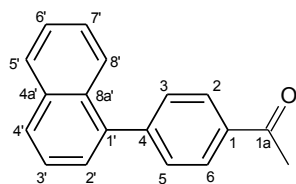
(C-3, 5), 129.4 (C-4'), 129.7 (C-2, 6), 130.7 (C-6'), 135.5 (C-1), 143.6 (C-4), 156.5 (C-2'), 197.8 ( $\underline{C}(O)CH_3$ ). MS (EIMS)  $m/z$  (%): 211 (100%), 168 (63%), 226 [ $M^+$ ] (54%), 139 (19%), 227 [ $M^+ + 1$ ] (11%), 160 (9%), 152 (6%). IR (neat): 3001, 2956, 2833, 1670, 1601, 1456, 1265, 1238, 1186, 1166, 1003  $cm^{-1}$ .

#### 5.4.14 Synthesis of 4-(2-methoxyphenyl)-nitrobenzene (**269**)



Following general procedure F, 2-(2-methoxyphenyl)benzo-1,3,2-diazaborole **3** (0.30 g, 1.34 mmol) was reacted with 4-bromonitrobenzene **261** (0.18 g, 0.89 mmol) to afford **269** as a white powder (0.17 g, 85%): mp 62-63 °C (lit.<sup>3</sup>: 61-63 °C).  $^1H$  NMR (400 MHz,  $CDCl_3$ )  $\delta$ : 3.86 (s, 3H), 7.02-7.11 (m, 2H), 7.35 (dd,  $J = 7.5, 1.7$  Hz, 1H), 7.38-7.45 (m, 1H), 7.71 (d,  $J = 8.8$  Hz, 2H), 8.20 (d,  $J = 8.8$  Hz, 2H).  $^{13}C\{^1H\}$  NMR (100 MHz,  $CDCl_3$ )  $\delta$ : 55.5 ( $OCH_3$ ), 111.4 (C-3'), 121.1 (C-5'), 123.1 (C-3, 5), 128.3 (C-1), 130.1 (C-4'), 130.3 (C-2, 6), 130.6 (C-6'), 145.4 (C-4), 146.6 (C-2), 156.4 (C-2'). MS (EIMS)  $m/z$  (%): 229 [ $M^+$ ] (100%), 139 (53%), 152 (28%), 128 (21%), 230 [ $M^+ + 1$ ] (10%). IR (neat): 2962, 2937, 2836, 1601, 1510, 1480, 1456, 1346, 1231, 1177, 1123, 1022, 1005  $cm^{-1}$ .

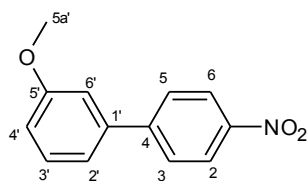
#### 5.4.15 Synthesis of 1-[4-(1-naphthalenyl)]-ethanone (**271**)



Following general procedure F, 2-(1-naphthyl)benzo-1,3,2-diazaborolidine (**183**) (0.30 g, 1.23 mmol) was reacted with 4-bromoacetophenone **263** (0.16 g, 0.82 mmol) to afford **271** as colourless crystals (0.19 g, 94%) mp 102-103 °C (lit.<sup>7</sup>: 102-103 °C):  $^1H$  NMR (400 MHz,  $CDCl_3$ )  $\delta_H$ , ppm: 2.70 (s, 3H), 7.42-7.50 (m, 2H), 7.50-7.60 (m,

2H), 7.63 (d,  $J = 8.3$  Hz, 2H), 7.86 (d,  $J = 8.4$  Hz, 1H), 7.93 (t,  $J = 9.5$  Hz, 2H), 8.11 (d,  $J = 8.5$  Hz, 2H).  $^{13}\text{C}\{^1\text{H}\}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{C}}$ , ppm: 26.6 ( $\text{C}(\text{O})\underline{\text{C}}\text{H}_3$ ), 125.3 (C-2'), 125.5 (C-5'), 125.9 (C-4'), 126.3 (C-8'), 126.9 (C-3'), 128.35 (C-7'), 128.41 (C-6'), 130.31 (C-5), 131.2 (C-1), 133.8 (C-8a'), 136.0 (C-4), 139.0 (C-1'), 145.81 ( $\underline{\text{C}}(\text{O})\text{CH}_3$ ). MS (EIMS)  $m/z$  (%): 231 (100%), 246 [ $\text{M}^+$ ] (72%), 202 (64%), 203 (41%), 247 [ $\text{M}^+ + 1$ ] (14%), 201 (12%). IR (neat): 2923, 2852, 1681, 1604, 1589, 1504, 1396, 1356, 1309, 1268, 1255, 1181, 1112, 1016  $\text{cm}^{-1}$ .

#### 5.4.16 Synthesis of 4-(3-methoxyphenyl)-nitrobenzene (**272**)

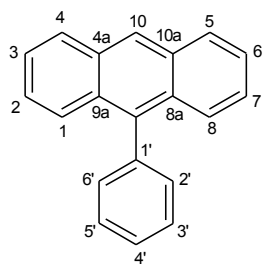


Following general procedure F, 2-(3-methoxyphenyl)benzo-1,3,2-diazaborole (0.30 g, 1.34 mmol) was reacted with 4-bromonitrobenzene **261** (0.18 g, 0.89 mmol) to afford **272** as white crystals (91%): mp 86-87 °C (lit.<sup>t</sup>: 86-87 °C).  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{H}}$ , ppm: 3.90 (s, 3H), 7.00 (dd,  $J = 8.1, 2.3$  Hz, 1H), 7.13-7.7.17 (m, 1H), 7.19-7.24 (m, 1H), 7.43 (t,  $J = 8.0$  Hz, 1H), 7.74 (d,  $J = 8.8$  Hz, 2H), 8.31 (d,  $J = 8.9$  Hz, 2H).  $^{13}\text{C}\{^1\text{H}\}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{C}}$ , ppm: 55.4 (C-5a'), 113.2 (C-4'), 114.1 (C-2'), 119.8 (C-6'), 124.0 (C-3,5), 127.8 (C-2, 6), 130.2 (C-5'), 140.2 (C-4), 147.2 (C-1), 147.4 (C-1'), 160.1 (C-3'). MS (EIMS)  $m/z$  (%): 229 [ $\text{M}^+$ ] (100%), 139 (53%), 171 (49%), 199 (48%), 140 (42%), 152 (28%), 128 (21%), 230 [ $\text{M}^+ + 1$ ] (10%). IR (neat): 2947, 2842, 1585, 1508, 1468, 1430, 1342, 1325, 1304, 1292, 1188, 1160, 1020  $\text{cm}^{-1}$ .

<sup>t</sup> Seganish, W. M.; DeShong, P. J. *Org. Chem.* **2004**, 69, 6790.

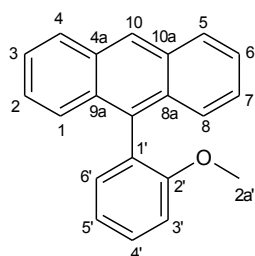


### 5.4.17 Synthesis of 9-phenylanthracene (**277**)



Following general procedure F, 2-phenylbenzo-1,3,2-diazaborole (**178**) (0.29 g, 1.49 mmol) was reacted with 9-bromoanthracene (**273**) (0.26 g, 0.99 mmol) to afford **277** as colourless plates-like crystals (0.19 g, 75%): mp 155-157 °C (lit.<sup>u</sup>: 153-155 °C). <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>) δ<sub>H</sub>, ppm: 7.32-7.42 (m, 2H), 7.42-7.53 (m, 4H), 7.53-7.65 (m, 3H), 7.70 (d, *J* = 8.79 Hz, 2H), 8.07 (d, *J* = 8.45 Hz, 2H), 8.52 (s, 1H). <sup>13</sup>C{<sup>1</sup>H} NMR (100 MHz, CDCl<sub>3</sub>) δ<sub>C</sub>, ppm: 125.1, 125.3, 126.5, 126.8, 127.4, 128.3, 128.3, 130.2, 131.2, 131.3, 137.0, 138.8. MS (EIMS) *m/z* (%): IR (neat): 3051, 2923, 1596, 1494, 1442, 1411, 1357, 1312, 1220, 1166, 1015 cm<sup>-1</sup>.

### 5.4.18 Synthesis of 9-(2-methoxyphenyl)-anthracene (**275**)



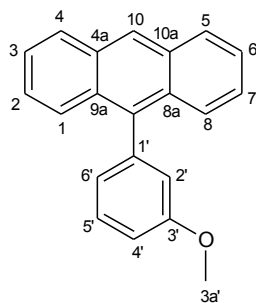
Following general procedure F, 2-(2-methoxyphenyl)benzo-1,3,2-diazaborole (0.30 g, 1.34 mmol) was reacted with 9-bromoanthracene **275** (0.26 g, 0.99 mmol) to afford **275** as cream-white powder (0.20 g, 72%): mp 177-178 °C (lit.<sup>v</sup>: 177-179 °C). <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>) δ<sub>H</sub>, ppm: 3.67 (s, 3H), 7.19-7.30 (m, 2H), 7.36-7.485 (m, 3H), 7.53 (t, *J* = 7.0 Hz, 2H), 7.58-7.65 (m, 1H), 7.75 (d, *J* = 8.7 Hz, 2H), 8.12 (d, *J* = 8.3 Hz, 2H), 8.55 (s, 1H). <sup>13</sup>C {<sup>1</sup>H} NMR (100 MHz, CDCl<sub>3</sub>) δ<sub>C</sub>, ppm: 55.7, 111.36, 120.7, 125.0, 125.2, 126.5, 126.7, 127.3, 128.4, 129.3, 130.4, 131.4, 132.8, 133.7,

<sup>u</sup> Nakamichi, N.; Kawabota, H.; Hayashi, M. *J. Org. Chem.* **2003**, 68, 8272.

<sup>v</sup> Yoshiba, T.; Hiroyuku, W.; Michiyo, N.; Tetsuya, S.; Masahiro, M.; Masakatsu, N. *J. Org. Chem.* **2003**, 68, 5236.

158.0. MS (EIMS)  $m/z$  (%): 119 (10), 126 (5), 178 (20), 191 (10), 239 (36), 284 [ $M^+$ ] (100), 285 [ $M^++1$ ] (16). IR (neat): 1805, 1597, 1493, 1462, 1431, 1356, 1242, 1220, 1108, 1047, 1019  $\text{cm}^{-1}$ .

#### 5.4.19 Synthesis of 9-(3-methoxyphenyl)-anthracene (**276**)



Following general procedure F, 2-(3-methoxyphenyl)benzo-1,3,2-diazaborole (0.30 g, 1.34 mmol) was coupled with 9-bromoanthracene **273** (0.26 g, 0.99 mmol) to afford **276** as colourless crystals (69%): mp 99-101 °C (lit.<sup>w</sup>: 99-100 °C).  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{H}}$ , ppm: 3.92 (s, 3H), 7.13-7.21 (m, 3H), 7.33-7.41 (m, 2H), 7.44-7.55 (m, 3H), 7.73 (d,  $J = 8.8$  Hz, 2H), 8.06 (d,  $J = 8.4$  Hz, 2H), 8.51 (s, 1H).  $^{13}\text{C}\{^1\text{H}\}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{C}}$ , ppm: 55.3, 113.2, 116.6, 123.7, 125.1, 125.3, 126.5, 126.8, 128.2, 129.3, 130.1, 131.3, 136.8, 140.2, 159.6. MS (EIMS)  $m/z$  (%): IR (neat): 3049, 3005, 1595, 1582, 1459, 1238, 1156, 1039, 1013  $\text{cm}^{-1}$ .

<sup>w</sup> Dikerman, C. S.; Klein, M. V.; George, B. *J. Org. Chem.* **1964**, 29, 3695.

# Chapter Four

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## 4. Introduction

### 4.1 Synthesis of Boronic acid and their Esters

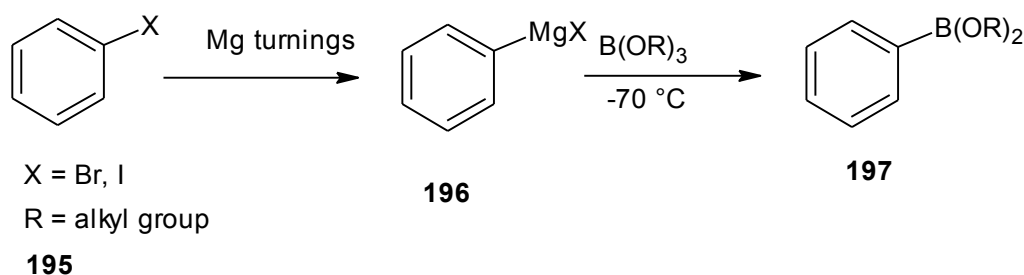
Arylboronic acid and their esters have been known for more than three decades yet their importance and versatility in organic synthesis are still recognised to date. Since their discovery in the early 1860s,<sup>1</sup> boronic acids and their esters have found a wide range of applications in different aspects such as synthetic intermediates in the preparation of biaryl compounds which are important structural components for various natural products, pharmaceutical compounds and biologically active compounds.<sup>2</sup> Boronic acids are also used as enzymes inhibitors,<sup>3</sup> as receptors and sensors for saccharides,<sup>4</sup> as well as bifunctional organic catalysts.<sup>5</sup>

The importance, versatility and the widespread applicability of boronic acids has demanded the development of efficient techniques for their synthesis. Through these developments, several methods have been discovered which make available a wide range of functionalised arylboronic acid and their esters with ease.<sup>6</sup> The following sections describe recent advances that have been achieved in the improvement of existing methods as well as the development of new routes to make available a large pool of functionalised aryl boronic acids.

#### 4.1.1 Metal-Halogen Exchange Method

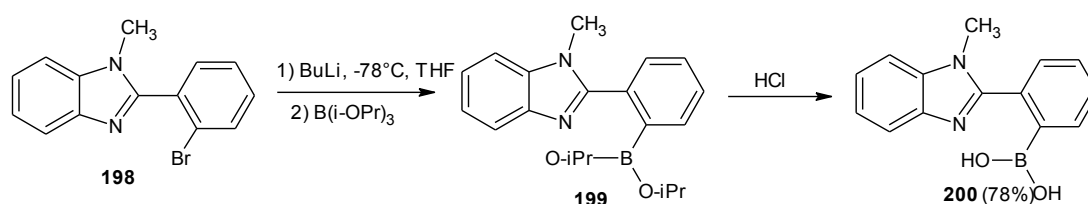
Metal-halogen exchange method is the oldest and the cheapest method to access boronic acids in reasonable yields. This method was discovered in the 1860s when a chemist, Frankland, reacted diethylzinc with triethylborate to produce triethylborane ( $\text{Et}_3\text{B}$ ), which upon oxidation in air, produced ethylboronic acid.<sup>1</sup> Building on the foundation described by Frankland, Melamed and co-workers reacted phenylmagnesium bromide with trimethylborate solution in their attempt to synthesise phenylboronic acid, however, this method provided the desired product in poor yields due to extensive formation of borinic acid side-products such as borinic derivatives.<sup>7</sup>

In order to avoid the formation of borinic side-products, Johnson and *et al.*<sup>8</sup> reported an improved procedure which involves the addition of phenylmagnesium bromide intermediate to a solution of tri-*n*-butylborate held at  $-70^{\circ}\text{C}$ . In the authors' point of view, the low temperature was intended to precipitate the nucleophilic phenylmagnesium bromide intermediate which eventually suppress its reactivity towards the formation of borinic acid side-products (**Scheme 55**).<sup>8</sup>



**Scheme 55**

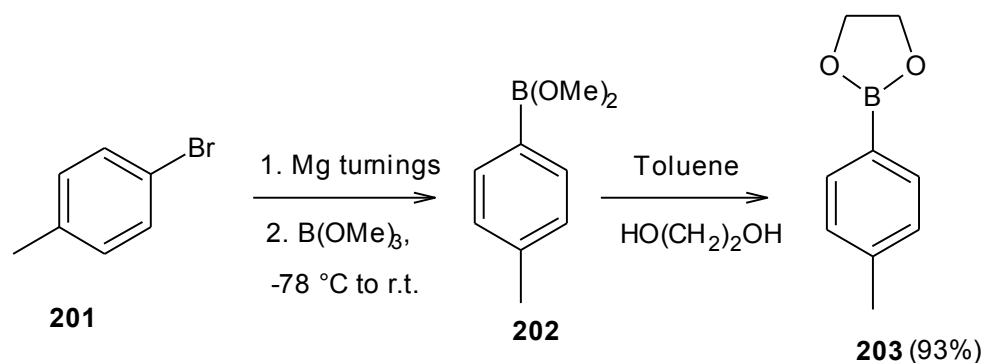
After this discoveries, this protocol has been successfully implemented in the synthesis of a range of boronic acids and their esters from the corresponding aryl halides.<sup>9</sup> This procedure leads to a mixture of magnesium salt, excess tri-alkylborate and the desired boronic ester.<sup>10</sup> To obtain free boronic acid, a standard workup procedure using a solution of an acid (usually 2M HCl) is required in order to hydrolyse the alkoxy leaving groups. Following the improved procedure, Blatch *et al.*<sup>11</sup> have successfully synthesised the intermediate boronic ester which upon acid hydrolysis furnished the desired free boronic acid in 78% yields (**Scheme 56**).<sup>11</sup>



**Scheme 56**

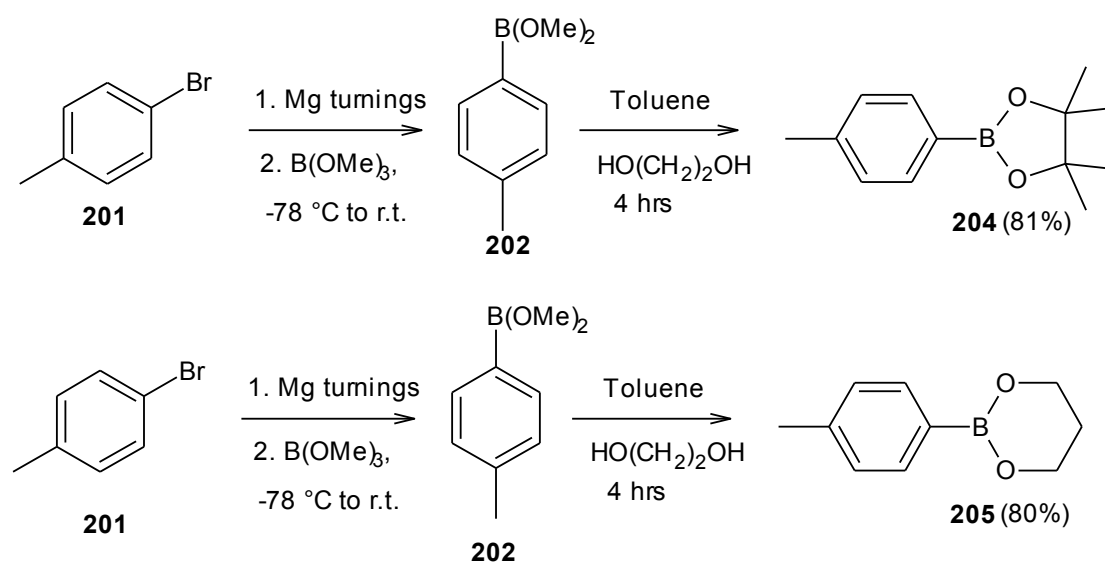
The drawback of the acid hydrolysis step is, however, that small water soluble boronic acids tend to dissolve in aqueous solution which in turn complicates the purification process and consequently leads to poor yields. To overcome these challenges, Wong and co-workers<sup>12</sup> disclosed an improved procedure which does not involve the aqueous workup step. In this approach, arylmagnesium bromide is treated with an excess solution of trimethylborate at  $-78^{\circ}\text{C}$ . After 3 hr of stirring, the solvent and an excess trimethylborate solution were evaporated affording the crude product as

white solid. The resulting white solid was heated under reflux in the presence of any 1,2-dialcohol compound in toluene affording the desired aryl boronic ester in excellent yields. (**Scheme 57**).<sup>12</sup>



**Scheme 57**

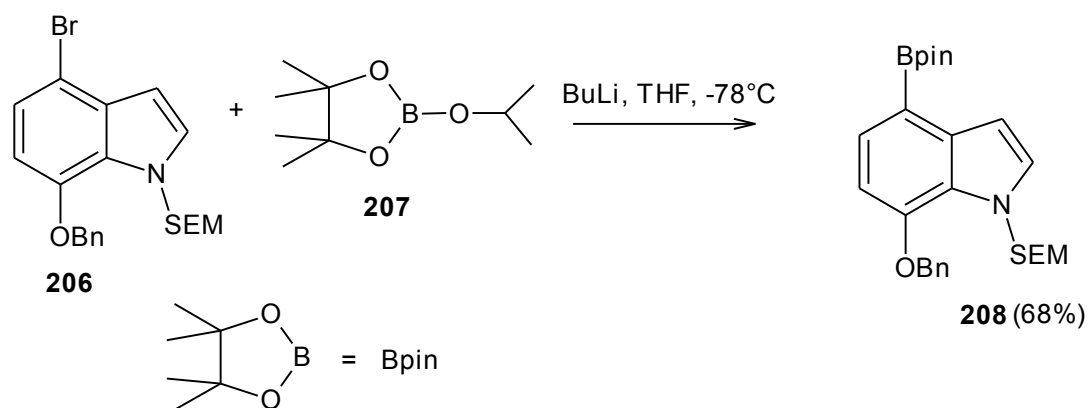
Several aryl-halides of markedly different structural features can be transformed into their corresponding arylboronic esters under these reaction conditions. This approach is not only limited to the use of ethylene glycol as a masking agent, other dialcohols such as pinacol and 1,3-propanediol can also be employed. For example, 2,4,6-trimethylboronic esters **204** and **205** were isolated in 81% and 80% yields from the related alcohols using the above-mentioned approach, respectively.<sup>12</sup>



**Scheme 58**

Although this procedure readily furnished the desired arylboronic esters after the cyclocondensation of the diol and the crude boronic acid, the evaporation of the

solvent and an excess trimethylborate solution is untidy and laborious. An improvement to this procedure was reported by Garg and co-workers,<sup>13</sup> in which their improved method involved the *in situ* quenching of an aryl metal intermediate with pinacol borate ester. However, this method afforded the desired product in only moderate yields (**Scheme 59**).<sup>13</sup>



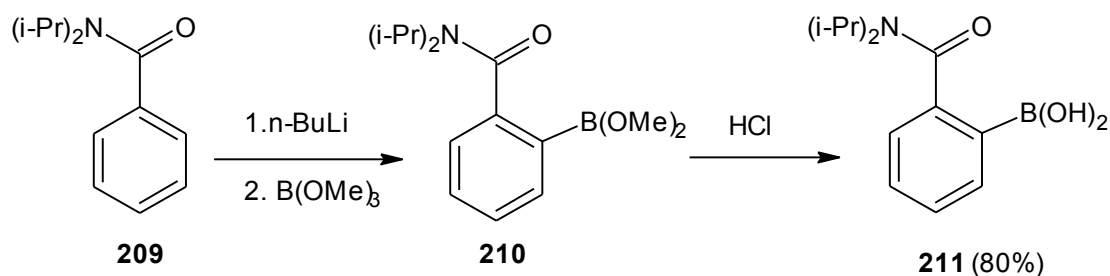
**Scheme 59**

Although the metal-halogen exchange methodology provides a suitable protocol to access a large pool of boronic acids and their esters, this method is limited only to the use of halogenated aromatics. In addition, only expensive bromo- and iodo-functionalised aryl halides are frequently used, whereas easily accessible and low-cost chlorinated and non-halogenated arenes are not accommodated in these procedures.<sup>6</sup>

#### 4.1.1.1 Directed Ortho-Metallation

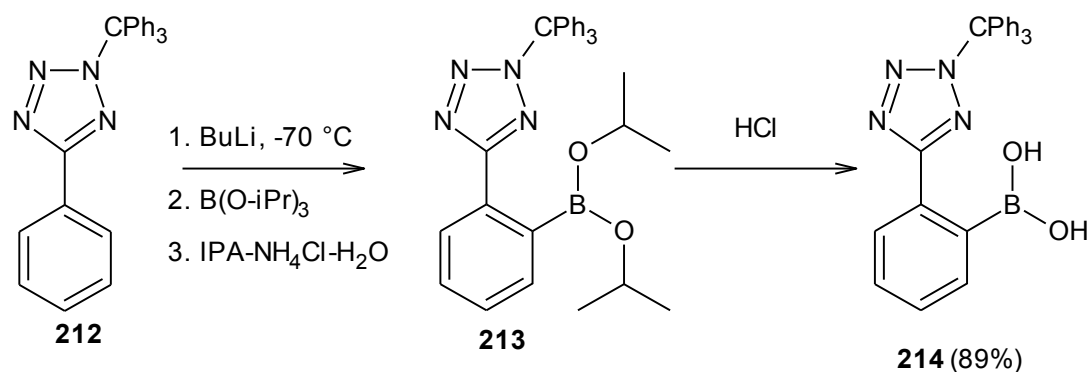
Alternatively, non-halogenated arenes could be transformed into their boronic acids provided they are functionalised with *ortho*-directing groups including amines, ethers and carbonyls. In this case, aryl compounds containing *ortho*-directing groups are treated with butyllithium at -78°C. The strong base (butyllithium) is intended to deprotonate the activated *ortho* position thus giving the *ortho*-aryllithium intermediate.<sup>6</sup> The resulting intermediate is subsequently quenched with trialkylborate solution to give the corresponding alkylated arylboronate esters which, upon acid hydrolysis, provide the desired arylboronic acids in excellent yields.<sup>6</sup>

The efficiency of this protocol has been demonstrated by a number of research groups. Mar and co-workers have successfully employed this procedure in their *ortho*-methylamino-phenyl boronic acid synthesis.<sup>14</sup> Sharp and Snieckus have also implemented this procedure in the preparation of *ortho*-carboxamido-phenylboronic acid (**Scheme 60**).<sup>15</sup>



**Scheme 60**

The reliability of the directed *ortho*-metallation method, in the preparation of boronic acids, is well demonstrated by its application in the pharmaceutical area where it has been shown to be a suitable method for the preparation of tetrazoleboronic acid, a precursor in the synthesis of the anti-hypertensive pharmaceutical drug Lasartan (**Scheme 61**).<sup>16</sup>



**Scheme 61**

The successful implementation of metal-halogen and *ortho*-metallation methods in the synthesis of arylboronic acids greatly relies on the formation of the highly reactive organomagnesium and organolithium intermediates.<sup>6</sup> These intermediates are well known for their air and moisture sensitivity which makes it a challenge to handle and manipulate them with ease.<sup>6</sup> In addition, these intermediates are highly nucleophilic

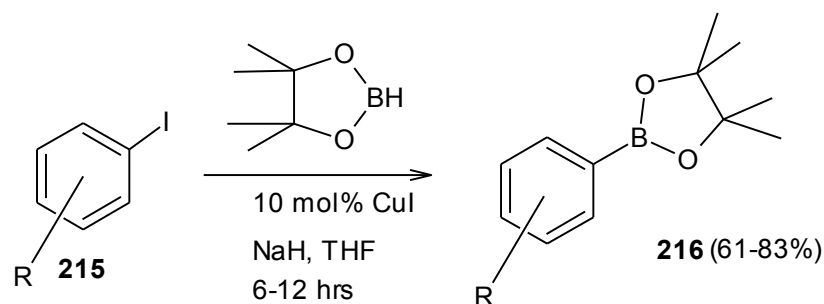
making them incompatible with a variety of functional groups such as unprotected hydroxyl, amines and carbonyl groups. For these reasons, metal-halogen and *ortho*-metallation methods have found limited applications in the synthesis of arylboronic acid and esters functionalised with substituents which are sensitive towards nucleophilic attack.<sup>6</sup> Recently, various methods have emerged particularly metal-catalysed techniques, which make available a large pool of functionalised aryl boronic esters from their corresponding aryl halides, including the well known non-reactive aryl chlorides, in excellent yields.<sup>17</sup> Most of these methods employ an air and moisture stable pinacolborane which has also been demonstrated, with a number of experiments, to be thermally stable in most organic solvents.<sup>18</sup> In addition, pinacolborane has been shown to be more reactive whilst it is less prone to disproportionation when compared to catecholborane.

## 4.1.2 Metal-Catalysed Borylation methodologies

### 4.1.2.1 Copper-Catalysed Borylation Reactions

In 2006, Zhu and Ma<sup>19</sup> reported that pinacolborane couples smoothly with a range of aryl iodides in the presence of 10% CuI and NaH (as a base) at room temperature, to provide the coupled aryl boronate ester products in good yields. Initially, triethylamine was used as a base, however, no desired coupled-product was observed. According to the authors, the failure of this reaction was ascribed to the weak basicity of Et<sub>3</sub>N.<sup>19</sup> As a consequence, stronger bases such as <sup>t</sup>BuOK, Cs<sub>2</sub>CO<sub>3</sub> and NaHMDS were also examined; however, none of these bases gave the desired product in good yields. Excellent yields were reported when NaH was used; nonetheless, the authors did not give an explanation for this observed trend. A variety of aryl iodides with different substituents were transformed to their corresponding aryl boronate esters in 61-83% yields under these optimised reaction conditions (**Scheme 62**).<sup>19</sup>

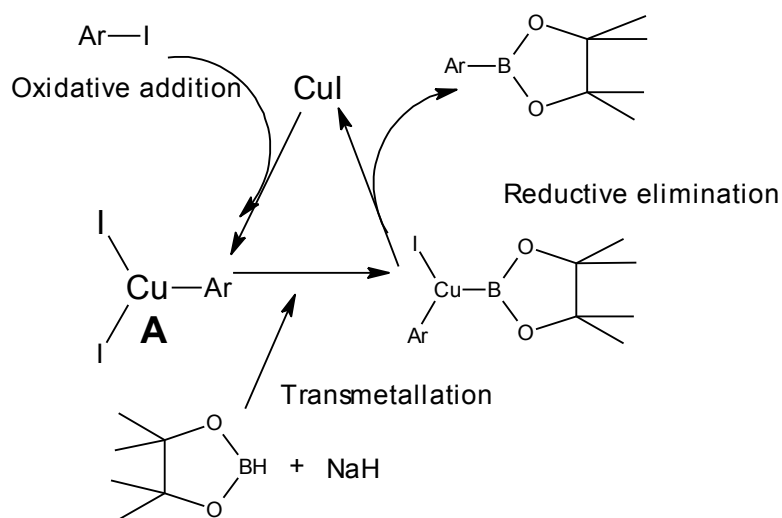




R = Ph, OMe, CF<sub>3</sub>, *t*-BuO<sub>2</sub>C, OH

**Scheme 62**

To account for the coupling reaction, Zhu and Ma proposed a mechanism which closely resembles the catalytic cycle suggested for Ullmann and Miura-Masuda type coupling reactions (**Figure 49**). In the mechanism, the carbon-iodide bond of an aryl iodide is oxidatively added to the CuI centre affording Cu(III) intermediate **A**.<sup>19</sup> This step is followed by the deprotonation of pinacolborane which subsequently facilitates the transmetalation of the deprotonated species to the metal centre. Finally, the reductive elimination step releases the desired coupled-aryl boronate ester and regenerates the catalyst for another cycle (**Figure 49**).<sup>19</sup>



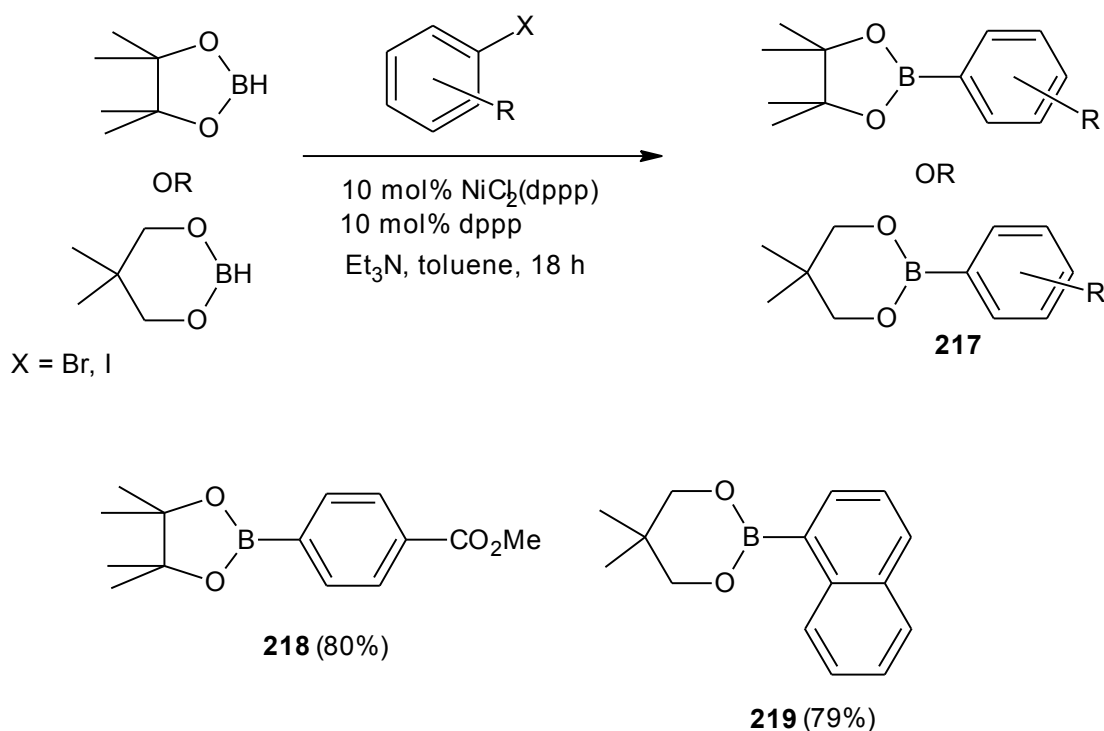
**Figure 49: pinacolboronylation of iodobenzene**

Although this method provides an easy and a milder route for the conversion of aryl iodides to their corresponding arylboronate esters, this protocol is only limited to the use of more reactive iodoarenes. Aryl bromides were demonstrated to be unsuitable electrophiles under these reaction conditions. A modification to this procedure was

reported by Rosen and co-workers<sup>20</sup> in their nickel-catalysed pinacolborylation and neopentylglycolborylation of aryl bromides and iodides.

#### 4.1.2.2 Nickel-Catalysed Borylation Reactions

According to Rosen *et al.*<sup>20</sup> the treatment of pinacolborane or neopentylglycolborane with aryl bromide or iodide in the presence of a catalytic amount of  $\text{NiCl}_2(\text{dppp})$  and triethylamine as a base in refluxing toluene furnished, after the purification step, the desired esters in excellent yields (**Scheme 63**).



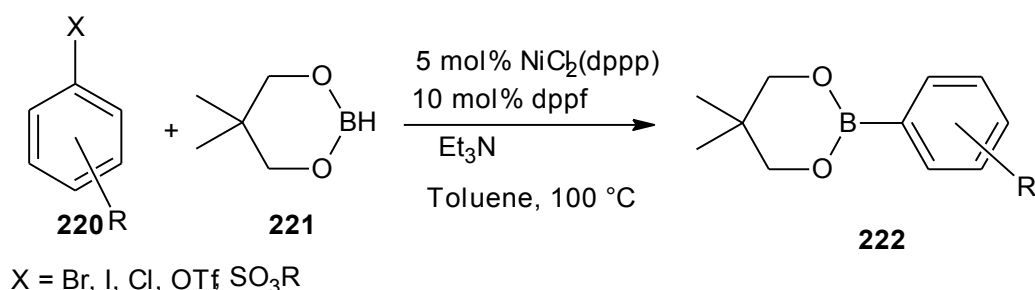
**Scheme 63**

Attempts to use aryl chlorides as electrophiles failed to give the corresponding arylpinacolborate esters. This observation was, as it is well documented in the literature, ascribed to slow oxidative addition to the metal of the carbon-chlorine bond.<sup>20, 21</sup> The solution to these challenges was recently reported by Moldoveanu *et al.*<sup>22</sup> and Knochel *et al.*<sup>23</sup> with the use of the nickel catalyst with mixed ligands, especially  $\text{NiCl}_2(\text{dppp}^1)/\text{dppf}^2$ , which significantly improves the efficiency of the nickel-catalysed neopentylglycolborylation reaction. With this new system, a variety

<sup>1</sup> Dppp: 1,3-Bis (diphenylphosphino)propane

<sup>2</sup> Dppf: 1,1'-Bis (diphenylphosphino) ferrocene

of aryl chloride, even the less reactive aryl sulfonates,<sup>24</sup> were smoothly neopentylglycolborylated to the corresponding aryl neopentylglycolboronate esters (**222**) in less than 72 hr (**Scheme 64**).<sup>22, 23</sup>

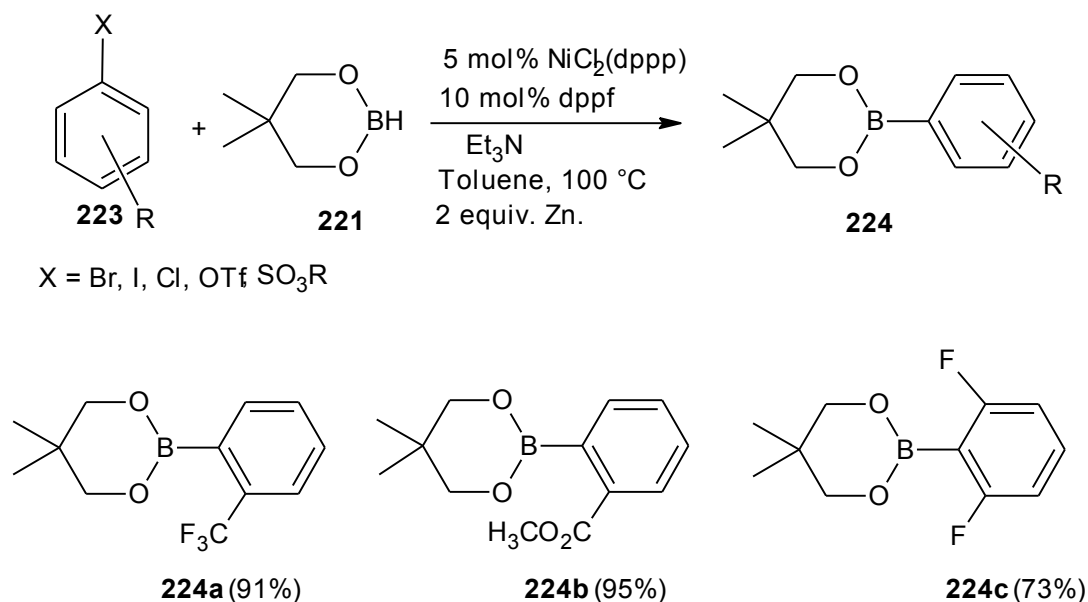


**Scheme 64**

The use of mixed ligands to accelerate the nickel-catalysed neopentylglycolborylation reactions was a great contribution to the development of nickel-catalysed borylation reactions. In addition to its effectiveness, Moldoveanu and co-workers<sup>25</sup> have recently reported that this methodology is also a superior protocol for the neopentylglycolborylation of *ortho*-substituted aryl halides (a reaction which has been describe on many occasions to be unsuccessful) with the aryl iodides reaching maximum conversion in few hours, whereas aryl bromide and chloride counterparts required longer reaction times.<sup>25</sup>

The desire to improve the nickel-catalysed neopentylglycolborylation was recognised by Leowanawat and *et al.*<sup>26</sup> when they realised that this transformation takes an unnecessarily longer time to completion, which in turn, has been reported to facilitate the formation protodeborated side-products. As a result, the group developed an improved zero-valent metal activated neopentylglycolborylation procedure. In this case, aryl halides are neopentylglycolborated under normal neopentylglycolborylation conditions except that a small amount of zero-valent metals such as Zn, Al, Ca and Mg are added to the reaction mixture.<sup>26</sup> The addition of these metals to the reaction mixture has been reported to greatly accelerate the neopentylglycolborylation reaction and also improves the yields of the desired products. Due to the limited mechanistic studies on the nickel-catalysed neopentylglycolborylation in the literature, the authors were unable to rationalised the role of these metals in accelerating the reaction rate.<sup>26</sup>

However, they tentatively presume that these metals reduce the Ni(II) pre-catalyst to its active form which in turn facilitates the oxidative addition of the aryl halide to the metal centre. With these modifications, the less reactive *ortho*-substituted aryl chlorides and bromides, which were previously reported to require more than 72 hr for moderate conversion, were borylated in less than 1 hour in excellent yields (Scheme 65).<sup>26</sup>

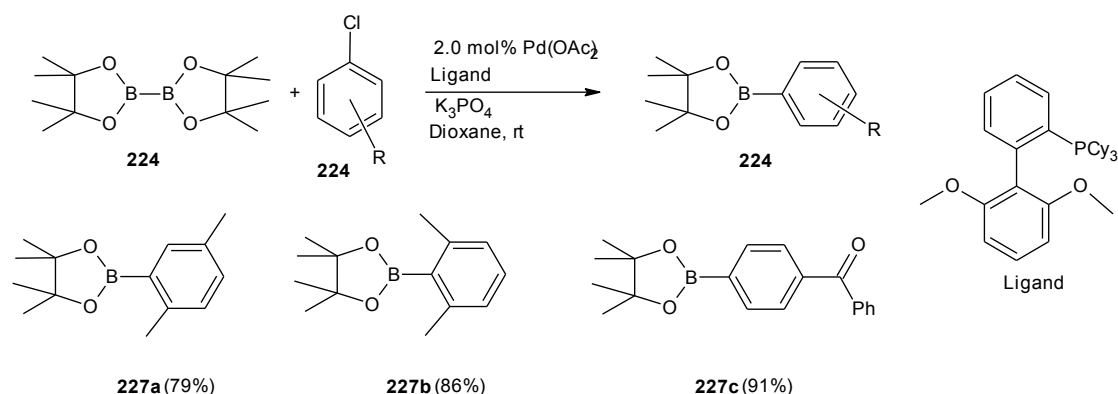


**Scheme 65**

#### 4.1.2.3 Palladium-Catalysed Borylation Reactions

Palladium catalysts have also been shown to affect the borylation reaction of arenes in the presence of triethylamine as a base. In 2004, Broutin and *et al.*<sup>27</sup> reported an efficient Pd-catalysed transformation of functionalised aryl bromides to their pinacolboronate esters in moderate to good yields.<sup>27</sup> Murata *et al.*<sup>28</sup> on the other hand have confirmed the efficiency of this methodology when they successfully employed this protocol in the pinacoloborylation of a range of aryl halides. However, in their original report it was pointed out that even though good yields of the desired pinacolborylated products are obtained using this method, this procedure is only suitable for the pinacolborylation of aryl iodides and bromides, whereas easily accessible and cost effective aryl chlorides are not reactive under these reaction conditions.<sup>28</sup>

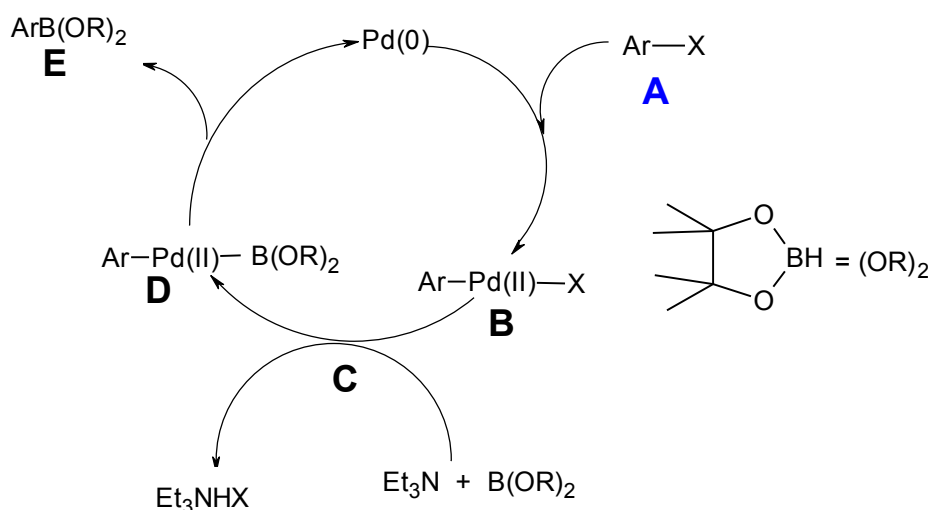
Billingsley and co-workers<sup>18</sup> subsequently released a report which describes the pinacolborylation of aryl chlorides in the presence  $\text{Pd}(\text{OAc})_2$  as a catalyst. According to these authors the treatment of aryl chloride with bis-(pinacolato)diboron under the influence of  $\text{Pd}(\text{OAc})_2$ , potassium acetate and dialkylphosphinobiphenyl ligand, furnished the expected pinacolborylated aryl esters in high yields (**Scheme 66**).<sup>18</sup>



**Scheme 66**

In 2008, Billingsley and *et al.* further extended their studies to the borylation of aryl halides with pinacolborane. In this study, a range of aryl halides with markedly different structures were smoothly converted to their corresponding aryl pinacolborate esters using  $\text{PdCl}_2(\text{CH}_3\text{CN})_2$  as a catalyst.<sup>29</sup>

To account for the palladium-catalysed borylation of aryl halides in the presence of triethylamine as a base, Ishiyama and Masuda independently proposed the same mechanism (**Scheme 67**). In their proposal, the carbon-halide bond of an electrophile **A** oxidatively adds to the zero-valent Pd metal to form  $\text{Ar-Pd}(\text{II})\text{-X}$  adduct **B**, which immediately reacts with a pinacolborane ion (formed from the deprotonation of pinacolborane) to generate  $\text{Ar-Pd}(\text{II})\text{-B}(\text{OR})_2$  intermediate **D**. The desired product **E** is reductively eliminated from the Pd(II) centre in order to regenerate Pd(0) species for the next catalytic cycle (**Scheme 67**).



**Scheme 67**

The development of simple, efficient, economically viable, mild and highly yielding protocols for the synthesis of boronic acids and their esters is clearly indicative of the importance of these species in organic chemistry.<sup>30</sup> Certainly, boronic acids and their corresponding esters have long been known and have been demonstrated to be the most valuable nucleophilic coupling partners in the transition metal-catalysed carbon-carbon bond constructions.<sup>31</sup>

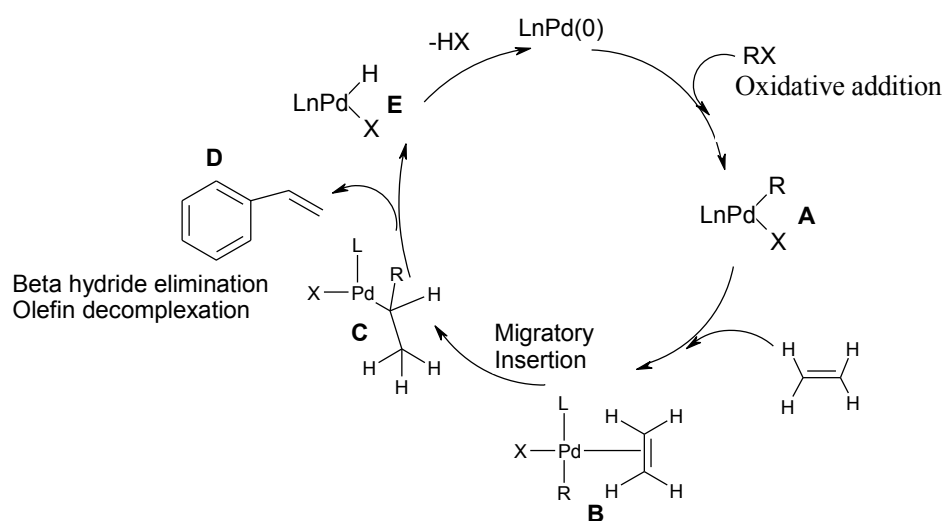
The transition metal-mediated cross-coupling reactions for the construction of carbon-carbon bonds, specifically the preparation of biaryls compounds, have emerged as one of the most powerful and versatile methodologies in organic synthesis. Biaryls are important structural components and are also precursors for the synthesis of natural products,<sup>32</sup> pharmaceutical compounds,<sup>33</sup> functional materials, polymers and agrochemical intermediates.<sup>34</sup> The significance of biaryls in organic synthesis has attracted considerable attention for the developments of new methods which make possible the formation of  $\text{C}_{\text{aryl}}\text{-C}_{\text{aryl}}$  bonds. As a consequence, numerous transition metal-mediated methods for the construction of  $\text{C}_{\text{aryl}}\text{-C}_{\text{aryl}}$  bonds have been developed and implemented such as Heck, Stille and Suzuki-Miyaura cross-coupling reactions.

## 4.2 Cross-Coupling Reactions

### 4.2.1 Heck Cross-Coupling Reaction

Heck<sup>35</sup> was the first to discover in 1968, that the treatment of an olefins with an *in-situ* generated phenylpalladium halide intermediates provided styrenes, through a  $\beta$ -hydride elimination process, in good yields (Scheme 4.15).<sup>36</sup> The discovery of this protocol provided an efficient procedure for the arylation of olefins at room temperature. To get an accurate and deep understanding of this reaction, Heck proposed a mechanism in which the organohalide is oxidatively added to the Pd (0) centre. This effect formally changes the oxidation state of the palladium metal from Pd(0) to Pd(II) which, in turn, leads to the formation of the organopalladium intermediate **A** (Scheme 68).<sup>37</sup>

The coordination of olefins to the palladium centre produces intermediate **B** which, during the migratory insertion step, rearranges in such a way that a new palladium–carbon bond is formed thus giving complex **C**. The desired coupled-product **D** is released from the metal centre through the process called  $\beta$ -hydride elimination or olefin decomplexation. To regenerate the active Pd(0) for the next catalytic cycle, the short-lived intermediate **E** is reduced by losing the HX moiety thus changing Pd(II) to the active Pd(0) complex (Scheme 68).<sup>37</sup>

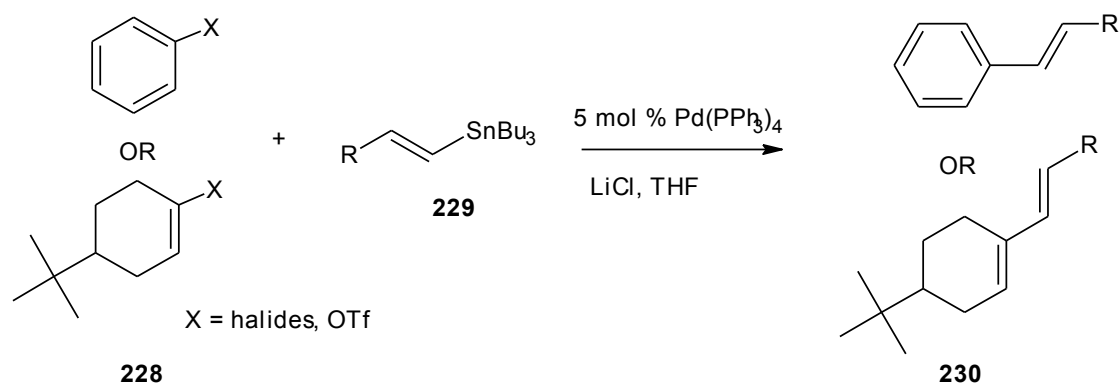


Scheme 68

After these reports by Heck, the Heck cross-coupling reaction became a popular method for the arylation of olefins in organic synthesis. A number of olefins with markedly different structures and steric requirements were demonstrated to be suitable nucleophiles under the reported reaction conditions.<sup>38</sup>

#### 4.2.2 Stille Cross-Coupling Reaction

In 1979, Stille and co-workers documented, in a series of papers, that the reaction of organostannanes with alkenyl and aryl halides or triflates, in the presence of Pd(0) as a catalyst, led to the formation of new carbon-carbon bonds between the two organic moieties (**Scheme 89**).<sup>39</sup>



**Scheme 68**

Since its discovery, this methodology has been applied in the synthesis of several vinyl and aromatic compounds and has emerged as one of the most popular in the construction of carbon-carbon bonds.<sup>40</sup> Although Stille cross-coupling reactions have emerged as one of the powerful transition metal-catalysed carbon-carbon bond forming methodologies, the difficulties encountered during the purification of the desired products and the toxicity of tin by-products has presented a barrier for the application of this protocol in the synthesis of pharmaceutical and natural products.<sup>40</sup>

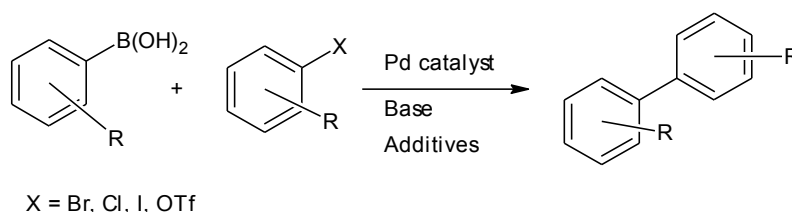
Alternatively, the transition metal-mediated carbon-carbon bond formation can also be achieved with the use of organoboron compounds as nucleophilic coupling partners.<sup>41</sup> This reaction, formally known as the Suzuki-Miyaura cross-coupling reaction, has become the most versatile in organic synthesis, particularly, because of 1) the ease with which the organoborane compounds are obtained, 2) the degradation



of these species into the environmentally friendly boric acid, 3) the mildness of the reaction conditions which in turn allows for the tolerance of numerous functional groups, and finally, 4) the general applicability of the reaction conditions.<sup>42</sup>

### 4.2.3 The Suzuki-Miyaura Cross-Coupling Reactions

The Suzuki-Miyaura cross-coupling reaction was discovered in 1979 by Suzuki and co-workers when they observed that substituted alkenyl and arylboronic acid and their corresponding esters are coupled with organic halides or triflates in the presence of palladium catalyst and a base at elevated temperatures (**Scheme 70**).<sup>43</sup> After these discoveries, several arylboronic acid and their esters with markedly different structures and steric requirements were reacted with a range of aryl halides in the presence of different palladium/ligand combination in order to assess the scope and limitations of this methodology.<sup>44</sup>



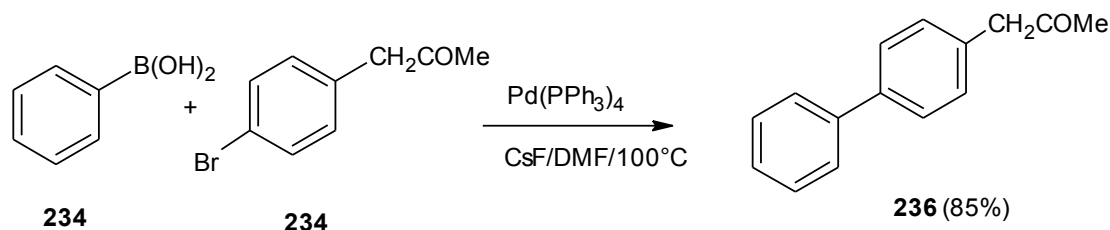
**Scheme 70**

A lot of effort in the Suzuki cross-coupling reaction has, in the past decade, been concentrated towards the development of new procedures that promote the cross coupling and broaden the scope of the reaction.<sup>45</sup> Through these efforts, tremendous progress has been achieved towards effective ligands,<sup>46</sup> solvents, bases, polymer-bound palladium catalyst and recently the use of nickel catalysts that enhances the efficiency of this cross-coupling reaction.<sup>47</sup>

In the following sections attention is focused on the progress that has recently been achieved in the improvement of the Suzuki-Miyaura cross-coupling reactions. Initially, the advancement and the current research focus on the palladium mediated Suzuki cross-coupling will be looked at, this section will be followed by the nickel catalysed cross-coupling counts

### 4.3.1 The Palladium Catalysed Suzuki-Miyaura Cross-Coupling Reactions

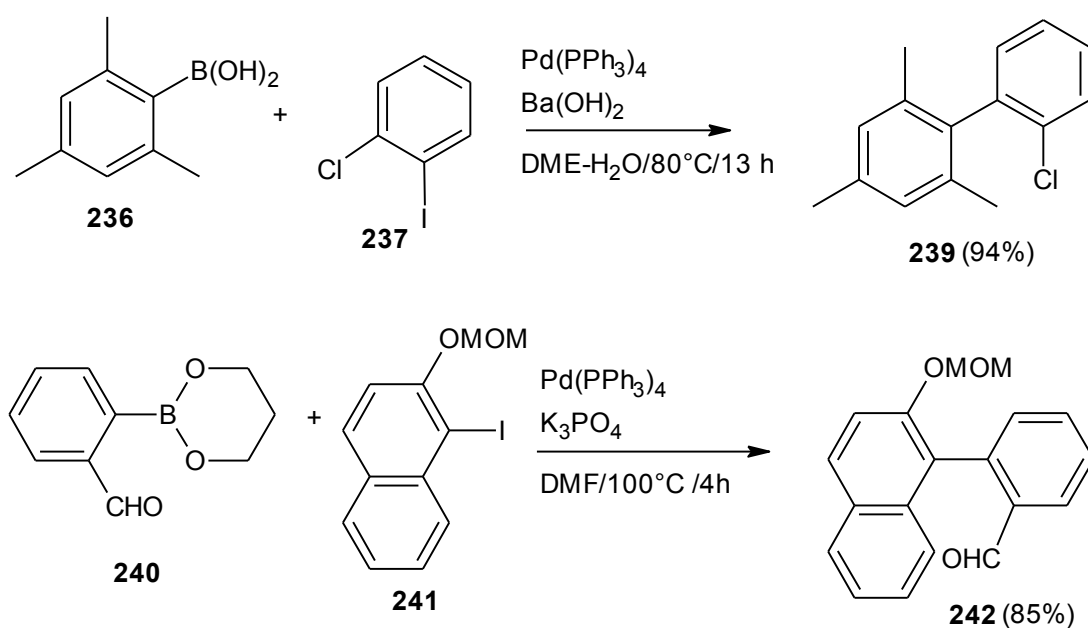
The first protocol for the synthesis of biaryls reported by Suzuki made use of an aqueous sodium carbonate, triphenylphosphine and benzene as base, catalyst and solvent, respectively.<sup>48</sup> Under these reaction conditions, phenylboronic acid was coupled with a range of aryl bromides and iodides giving the corresponding coupled-products selectively in moderate to good yields.<sup>48</sup> After this report, different advancements were made in order to enhance the efficiency of the Suzuki cross-coupling reaction. For example, Wright *et al.* reported in 1994 that the reaction of phenylboronic acid with the brominated arene proceeded successfully under the influence of a catalytic amount of  $\text{Pd}(\text{PPh}_3)_4$  in the presence of CsF and DME as a base and a solvent, respectively (**Scheme 71**).<sup>49</sup>



**Scheme 71**

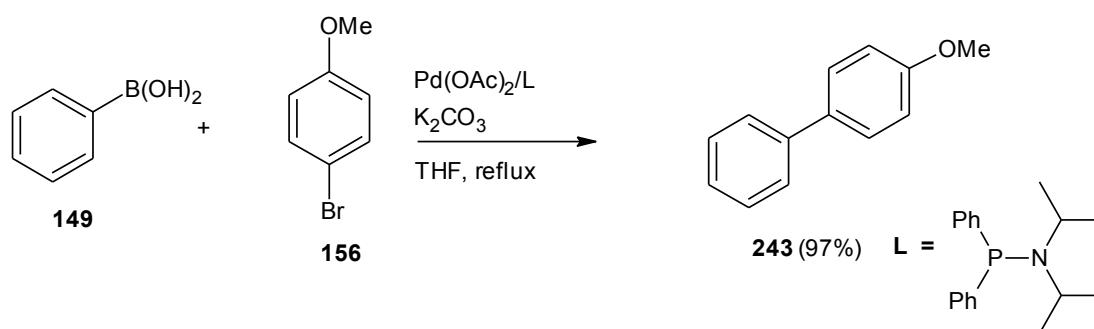
Sterically hindered boronic acids and their esters substituted at the 2-position or functionalised with electron-withdrawing substituents are usually poor nucleophilic coupling partners due to either the steric hindrance or susceptibility to hydrolytic deboration. To overcome these difficulties, Watanabe and co-workers made use of  $\text{Ba}(\text{OH})_2$  and  $\text{K}_3\text{PO}_4$  as bases (**Scheme 72**).

According to the authors, these strong bases are crucial for the cross-coupling reaction of sterically hindered nucleophilic coupling partners as they increase the electrophilicity of the organic group attached to the boron atom, therefore, accelerating the translocation process.<sup>50</sup>



**Scheme 72**

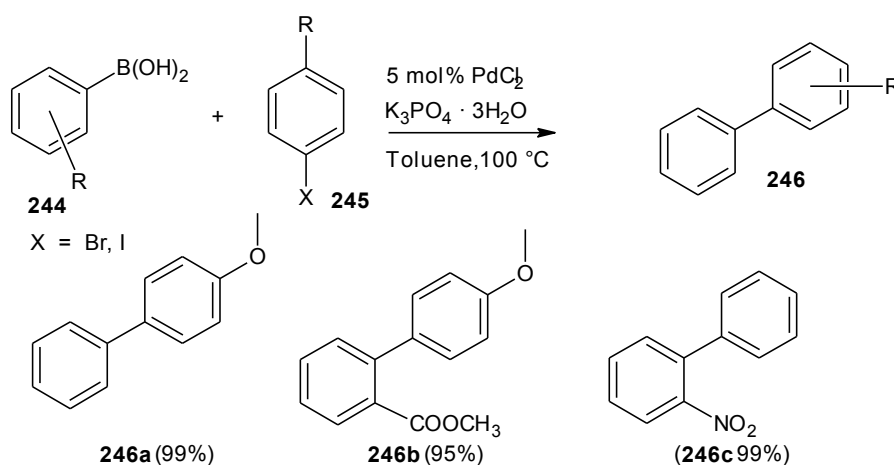
The observation made by Watanabe and *et al.* was also confirmed by Zhang and Chan,<sup>51</sup> in 1996, when they realised the remarkable effect of using strong bases in the cross-coupling reaction of sterically bulky arylboronic acids. Zhang and Chan reported that in the presence of a strong base such as potassium *t*-butoxide, *ortho*-disubstituted boronic acids are smoothly coupled with aryl halides without any by-products being formed.<sup>51</sup> Stronger inorganic bases such as TIOH or  $\text{Ti}_2\text{CO}_3$  are usually toxic or are usually moisture and air sensitive in the case of BuLi or potassium *t*-butoxide, which consequently limits the applicability of these protocols in the preparation of substituted biaryls industrially.<sup>52</sup> Interested in the development and the improvement of the Suzuki cross-coupling reaction conditions, Cheng *et al.* investigated, in 2003, the effect of electron-rich phosphine based-ligands on the rate of the cross-coupling reactions.<sup>53</sup> Their results revealed that the treatment of phenylboronic acid with aryl bromides in the presence of electron-rich ligands accelerate the cross-coupling reaction yielding the coupled-products in excellent yields (**Scheme 73**). The authors reported that the electron-rich ligands accelerates the oxidative addition step which in turn facilitates the oxidation of the palladium metal making it easier for the carbon–halogen bond to be added to the metal centre.<sup>53</sup>



**Scheme 73**

The remarkable impact of the ligands in the improvement of the Suzuki cross-coupling reaction was further demonstrated by Bellina *et al.*<sup>54</sup> when they reported that the use of N- and P-based-ligands dramatically increases the efficiency of the Suzuki-Miyaura cross-coupling reaction. Even though the addition of the ligands has been reported, by several authors, to enhance the effectiveness of the Suzuki cross-coupling, most of these ligands are costly, air sensitive, they complicate the workup procedures as well as the purification of the desired products, which in turn significantly limits the widespread applicability of these procedures in the large scale production of biaryls.<sup>55</sup>

To overcome these obstacles, the Pan group<sup>55</sup> and several other researchers<sup>56, 57</sup> have recently developed and implemented the ligand-free Suzuki cross-coupling procedure for the synthesis of symmetrical and asymmetrical biaryls.<sup>58</sup>



**Scheme 74**

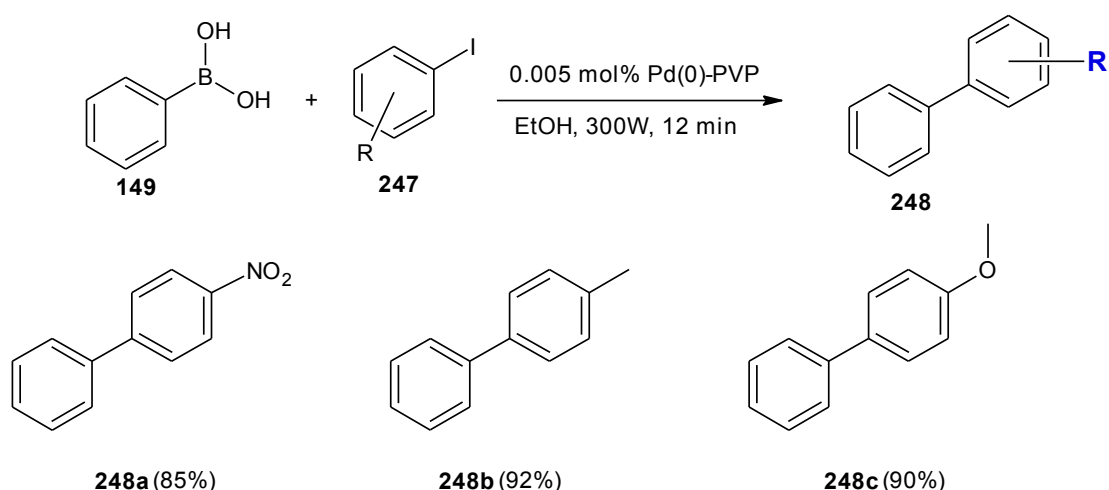
Pan *et al.*<sup>55</sup> demonstrated that the reaction of phenylboronic acids substituted with either the electron-withdrawing or electron-donating functionalities with aryl bromides and iodides proceeded, with great ease, in the presence 5 mol% PdCl<sub>2</sub> as a catalyst furnishing the desired coupled-products in yields of up to 99% (**Scheme 74**).<sup>55</sup> The ligandless Suzuki cross-coupling protocol has also been demonstrated recently by the Andrio group to be highly efficient for the preparation of both substituted and unsubstituted biaryls.<sup>57</sup> In this case, the treatment of the aryl boronic acid with aryl bromides, under the influence of 1 mol % Pd(OAc)<sub>2</sub>, affords the coupled-products in yields greater than 80% within 10 minutes.

Current research on the Suzuki cross-coupling arena has been devoted at the development and the application of palladium nanoparticles as the potential cross-coupling catalysts.<sup>59</sup> The use of nanoparticles in catalysis has been described to be advantageous (compared to the use of bulk catalysts) due to their increased surface area and their easy recovery allowing for better catalytic activity and multiple usage of the catalyst.<sup>60</sup> The application of nanoparticles in catalysis has attracted considerable attention for improvement and as consequence, several research groups have directed their research focus at investigating the scope and limitation of these newly discovered molecules.<sup>61</sup>

For instance, the Martins group has reported the use of Pd(0)-PVP nanoparticles in the preparation of biaryls. According to the authors, aryl boronic acids are efficiently coupled with aryl iodides in the presence of 0.005 mol% Pd(0)-PVP<sup>3</sup> catalyst and K<sub>2</sub>CO<sub>3</sub> base under the microwave irradiation furnishing the desired products in only 12 minutes (**Scheme 75**).<sup>60</sup>

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<sup>3</sup>PVP : poly(*N*-vinyl-2-pyrrolidone)



**Scheme 75**

In a related study, Lorenzo<sup>62</sup> recently (2012) investigated the influence of the size and shape of Pd nanoparticles on the efficiency of the Suzuki cross-coupling reaction. He and other research groups found that the rate of the catalytic activity increases with a decrease in the particles size. This behaviour was ascribed to their high surface-to-volume ratio which in turn increases the reaction site.<sup>62</sup>

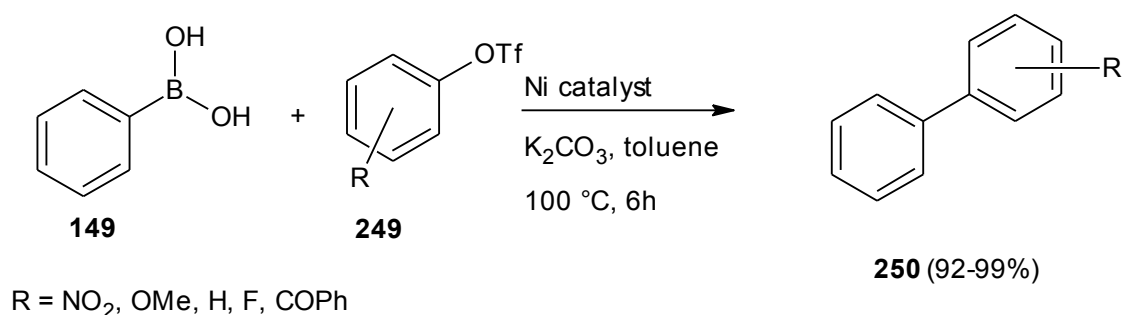
A vast number of palladium catalysts have been reported to mediate the Suzuki cross-coupling reaction in the literature. Palladium catalyst with bulky triphenylphosphine ligands such as Pd(PPh<sub>3</sub>)<sub>4</sub> and Pd(PPh<sub>3</sub>)<sub>2</sub> are commonly used in the Suzuki cross-coupling reaction because of their stability towards prolong heating. Ligandless palladium catalyst such as Pd(OAc)<sub>2</sub> and PdCl<sub>2</sub> have also been reported to be effective since they are more reactive and insensitive to air and moisture.

### 4.3.2 Nickel Catalysed Suzuki Cross-Coupling Reactions

The palladium-catalysed Suzuki cross-coupling reaction is one of the most efficient methodologies for the formation of aryl-aryl bonds. Tremendous progress in the development of various Pd catalyst has been achieved allowing the cross-coupling of aryl halides (including previously non-reactive aryl chlorides) with arylboronic acid to be highly efficient even under mild reaction conditions.<sup>48</sup> Even though this method has proven highly successful in the preparation of substituted biaryls, the high cost of both the Pd catalyst and the supporting ligands demanded an alternative protocol for the preparation of biaryls. Indeed, the longstanding search for a cheap, easily available and a highly reactive catalyst conducted by Percec and co-workers soon

revealed the effectiveness of nickel catalysts as an alternative to the mostly used Pd catalysts.<sup>63</sup>

In 1995, the Percec group reported, for the first time, the use of nickel catalyst in the Suzuki cross-coupling reaction.<sup>63</sup> Since this first report by Percec, several different nickel-based catalysts<sup>64-68</sup> have been reported to mediate the Suzuki cross-coupling reaction of aryl halides including previously non-reactive aryl chlorides<sup>69</sup> and aryl mesylates<sup>70</sup> under mild reaction conditions.<sup>70</sup> For instance, Fan *et al.*<sup>71</sup> have reported the application of easily accessible Ni(II)-(σ-aryl) complexes as the catalyst for the Suzuki cross-coupling reaction. Fan *et al.*<sup>71</sup> documented that the reactions of substituted aryltosylates with aryl boronic acids proceeded smoothly in the influence of a catalytic amount of Ni(PPh<sub>3</sub>)<sub>2</sub>(1-naphthyl)Cl and K<sub>2</sub>CO<sub>3</sub> as a base providing the desired product in excellent yields (**Scheme 76**).<sup>71</sup>



**Scheme 76**

## **4.4 Aims of Chapter Four**

Although palladium-catalysed Suzuki-Miyaura cross-coupling reaction is a well established methodology for the preparation of substituted biaryls, this method is dependent exclusively on the use of aryl boronic acids as nucleophilic coupling partners. There are only few publications in the literature which have reported the use of other organoborane derivatives that could be used in the Suzuki-Miyaura cross-coupling reaction. To the best of our knowledge, 2-arylbenzo-1,3,2-diazaborole derivatives have never been described in the cross-coupling reaction despite their profound Lewis acidity and stability which are advantageous during the transmetalation step.

The main objectives of this project are:

1. To improve the Suzuki-Miyaura cross-coupling reaction by expanding the scope of organoborane compounds to ultra-stabilised 2-arylbenzo-1,3,2-diazaborole as coupling partners.
2. To evaluate the potential suitability of these compound as the Suzuki coupling partner by reacting them with a range of aryl bromides bearing electron-withdrawing and electron-donating functionalities, in the preparation of substituted biphenyls
3. To compare yields of substituted biphenyls obtained using aryl boronic acids to those obtained using 2-arylbenzo-1,3,2-diazaborole as coupling partners.



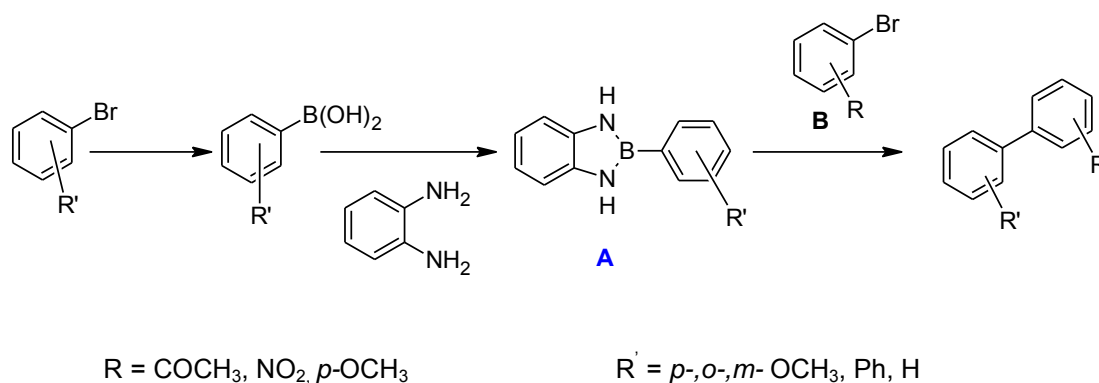
## 4.5 Results and Discussion

### 4.5.1 Preface

In chapter two, attention was directed at investigating the suitability of 2-alkyl/alkenylbenzo-1,3,2-diazaborole compounds as Suzuki coupling partners. It was found that these compounds are not only stable towards air and moisture when compared to the oxygenated analogues, but are also remarkable Suzuki coupling partners furnishing the desired coupled-product in excellent yields in or less than 20 minutes.

In chapter three, a lot of attention has been devoted to the assessment of the bonding parameters between the boron and the surrounding atoms in order to evaluate the charge density around the boron atom. From these studies, it was found that the intriguing properties displayed by 2-arylbenzo-1,3,2-diazaborole compounds are due to the enhanced  $\pi$ -interaction between the vacant  $2p_z$ -orbital on the boron atom and the  $\pi^*$ -orbital on the attached organic  $\pi$ -system. This enhanced  $\pi$ -interaction between the diazaborolyl group and the aromatic ring increases the charge density around the boron atom which in turn is believed to weaken the boron-carbon bond thus facilitating the transmetalation step during the cross-coupling processes.

This chapter is focused on the evaluation of the synthesised 2-arylbenzo-1,3,2-diazaborole compounds as potential Suzuki coupling partners. This evaluation will be achieved by reacting 2-arylbenzo-1,3,2-diazaborole compounds with various aryl bromides bearing either electron-withdrawing or electron-donating functionalities under the Suzuki cross-coupling reaction conditions (**Scheme 77**).



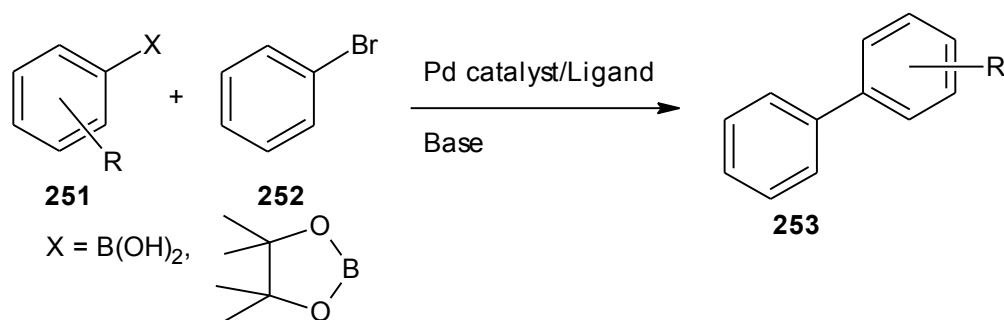
**Scheme 77**

The synthesis of the starting materials (arylboronic acids and 2-arylbenzo-1,3,2-diazaboroles) are covered in details in chapter three and will therefore not be duplicated in this chapter. In the section that follows, attention will be focused on the preparation of either symmetrical or non-symmetrical biaryls using 2-arylbenzo-1,3,2-diazaborolane compounds as nucleophilic coupling partners.

### 4.5.2 The Suzuki-Miyaura Cross-Coupling Reaction.

The carbon-carbon bond formation reactions have become one of the most important processes in organic chemistry.<sup>72</sup> One of these processes is the palladium-catalysed Suzuki-Miyaura cross-coupling reaction, which has become the most popular methodology for the construction of the carbon-carbon bonds of biaryls. The Suzuki-Miyaura cross-coupling reactions have proven to be the most efficient, versatile and frequently used transition metal-catalysed cross-coupling reactions for the preparation of both the symmetrical and asymmetrical biaryls,<sup>41</sup> which themselves have found diverse applications as liquid crystals, chiral ligands, structural components of pharmaceuticals,<sup>33</sup> natural products<sup>32</sup> and herbicides.<sup>73</sup>

The non-toxicity of the reagents and by-products,<sup>74</sup> and the mildness of these reaction conditions have attracted much attention for improvement. Consequently, several research groups have devoted their focus towards investigating the use of sophisticated ligands, solvents, bases and recently the use of polymer-bound palladium catalysts with the aim of improving these procedures. Despite these significant advances, the Suzuki-Miyaura cross-coupling reaction has, since its discovery, exclusively been based on the utility of aryl boronic acid and their corresponding oxygenated esters as the coupling partners (**Scheme 78**).

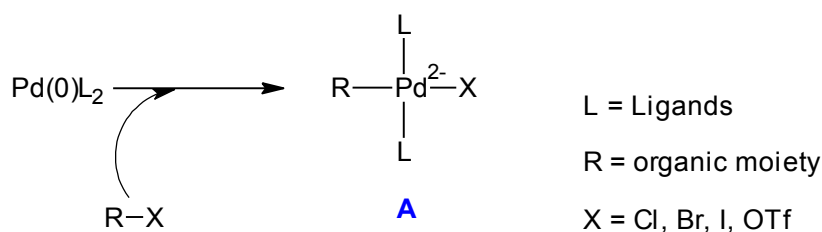


**Scheme 78**

To date, only few researchers have described the formation of carbon(aryl)–carbon(aryl) bonds with the use of other organoboron compounds as the nucleophilic coupling partners. It has only been recently that researchers have realised the desire to investigate other potential nucleophilic coupling partners in order to expand their scope thereby improving and generalizing this transformation.<sup>75</sup> Potassium heteroaryltrifluoroborate compounds have recently been demonstrated to be superior coupling partners that are advantageous compared to aryl boronic acids and their esters.<sup>76-78</sup>

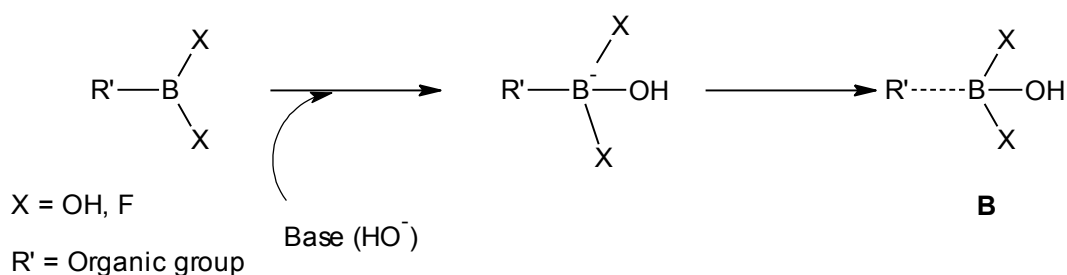
#### 4.5.2.1 Mechanism of the Suzuki-Miyaura Cross-Coupling Reaction.

The mechanism for the palladium-catalysed Suzuki cross-coupling reaction was first reported by Suzuki and Miyaura in 1985.<sup>79</sup> The mechanism was reported to involve the oxidation–transmetallation–reductive elimination sequences. The oxidation step has been set forward as the initial step of the mechanism, and has been shown to involve the addition of the organic halide to the zero-valent palladium centre to afford adduct **A** (Scheme 79).<sup>80, 81</sup>



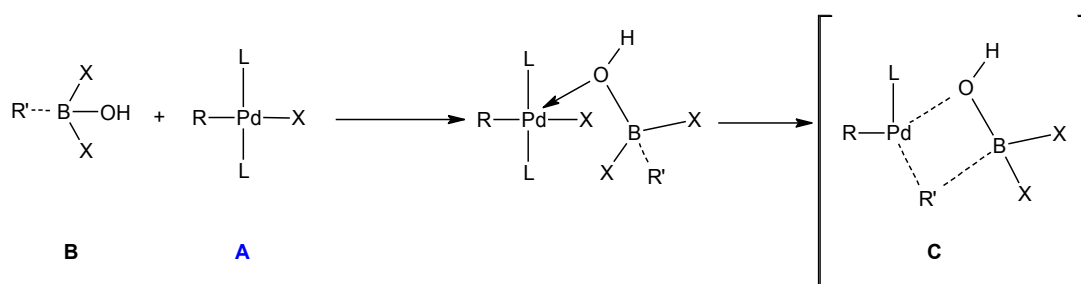
**Scheme 79**

During the transmetalation step, the organic moiety directly attached to the boron atom is transferred to the metal centre; however, extensive mechanistic studies have revealed that the transmetalation step greatly depends on the electron density of the participating organoboron compound.<sup>82</sup> The Soderquist group have reported that organoboron compounds that are more Lewis acidic (electron poor) undergo rapid complexation with the base which in turn increases the charge density on the boron atom (Scheme 6.4). This process has been reported to weaken the boron–carbon bond thus increasing the nucleophilicity of the attached organic group providing the organoboron complex **B** (Scheme 80).<sup>82, 83</sup>



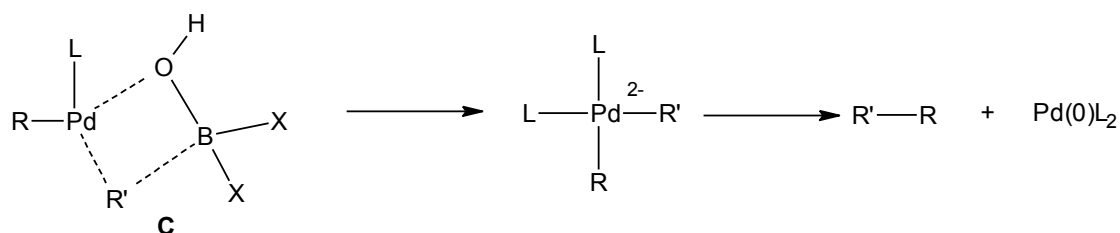
**Scheme 80**

The coordination of the palladium complex **A** with the organoboron complex **B** proceed through a four-centred transition state to afford complex **C** (**Scheme 101**).<sup>82</sup>



**Scheme 81**

During the reductive elimination step, the palladium complex **C** rearranges to locate the two organic moieties *cis* to each other. This step is followed by the elimination of the coupled-product from the metal centre which is accompanied by the reduction of the palladium from Pd(II) to Pd(0) (**Scheme 82**).



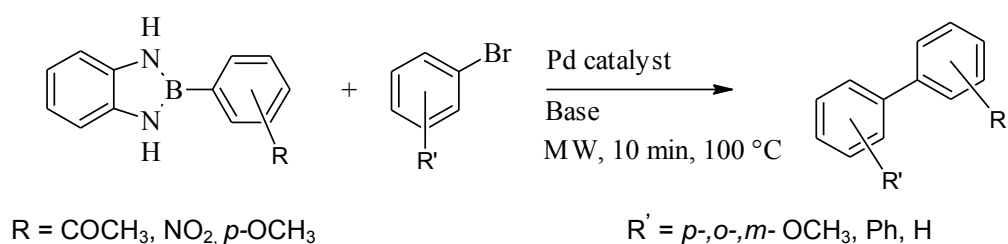
**Scheme 82**

According to the mechanism, it is apparent that the Lewis acidity of the organoboron compounds plays a crucial role in facilitating the transmetalation step. The greater the Lewis acidity of the organoboron compound the faster is the complexation with the base. The latter process is thought to increase the electron density donated to the vacant  $2p_z$ -orbital which in turn weakens the C–B bond thus accelerating the transmetalation step.<sup>82</sup>

In separate studies, Denk *et al.*<sup>84b</sup> and Hadebe<sup>84a</sup> independently reported that nitrogen-based organoborane compounds are electron rich when compared to their oxygenated-counterparts, as evidenced by higher degree of  $\pi$ -electrons back donated from the two chelating nitrogen atoms to the vacant  $2p_z$ -orbital of the boron atom. This observation was further supported by our UV-visible and fluorescence studies (Chapter 3) which showed that the vacant  $2p_z$ -orbital of the boron atom is indeed responsible for the extended  $\pi$ -communication between benzodiazaborolyl group and the attached organic  $\pi$ -system, indicating the electron density being donated to the vacant  $2p_z$ -orbital.<sup>85</sup>

Based on these rationalisations, we believe that the high electron density back donates from the two chelating nitrogen atom to the vacant  $2p_z$ -orbital would exert a considerable positive effect towards their reactivity during the transmetalation step. Because their enhanced charge density on the boron atom, these compounds are expected to undergo the transmetalation step with ease furnishing the desired coupled-products in excellent yields in shorter reaction times.

To the best of our knowledge, there are only few researchers who have directed their research focus towards improving the Suzuki cross-coupling reaction by investigating the utility of other organoborane compounds (other than arylboronic acid and their esters). Particularly, the application of nitrogen-based organoborane compounds (2-arylbenzo-1,3,2-diazaborole) have never been described as potential nucleophilic coupling partner in the Suzuki realm. This prompted us to investigate the Suzuki-Miyaura cross-coupling reaction of 2-arylbenzo-1,3,2-diazaborole compounds with aryl halides bearing electron-withdrawing or electron-donating functional groups (**Scheme 83**).

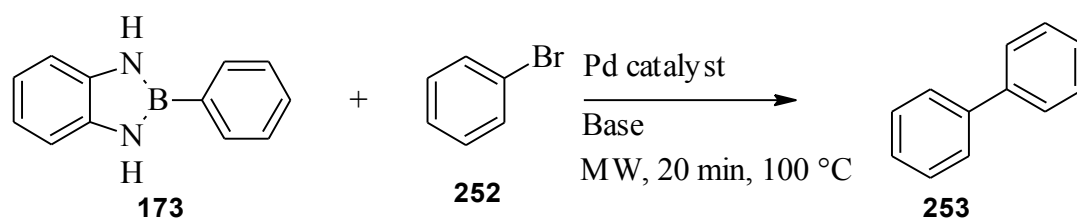


**Scheme 83**

Initially, an optimisation study was conducted on the cross-coupling reaction between the corresponding aryl bromides and the benzodiazaborolyl derivatives. In this study, 2-phenylbenzo-1,3,2-diazaborole was reacted with bromobenzene as an electrophilic coupling partner (Table 4.1). This reaction was repeated several times varying palladium catalysts (Table 4.1).

Encouraged by the effect of the microwave irradiation in our previous study (Chapter two), we thought that it would be logical to conduct these reactions under the influence of the microwave energy.<sup>86</sup>

**Table 4.1:** Optimisation study between 2-phenylbenzo-1,3,2-diazaborole **173** with bromobenzene, an optimal reaction conditions survey.



Entry	Pd Cat.	Ligand	Base	Yields (%) <sup>b</sup> <b>5</b>
1	PdCl <sub>2</sub>	None	none	0
2	PdCl <sub>2</sub>	PPh <sub>3</sub>	K <sub>3</sub> PO <sub>4</sub>	< 5
3	Pd (PPh <sub>3</sub> ) <sub>4</sub>	None	K <sub>2</sub> CO <sub>3</sub>	21
4	Pd (PPh <sub>3</sub> ) <sub>2</sub>	None	K <sub>2</sub> CO <sub>3</sub>	18
5	Pd (PPh <sub>3</sub> ) <sub>4</sub>	None	K <sub>3</sub> PO <sub>4</sub> ·H <sub>2</sub> O	10
6	Pd (PPh <sub>3</sub> ) <sub>2</sub>	PCy <sub>3</sub>	K <sub>3</sub> PO <sub>4</sub> ·H <sub>2</sub> O	33
7	PdCl <sub>2</sub>	PCy <sub>3</sub>	K <sub>3</sub> PO <sub>4</sub> ·H <sub>2</sub> O	< 5
8	Pd(OAc) <sub>2</sub>	PPh <sub>3</sub>	K <sub>2</sub> CO <sub>3</sub>	51
9	Pd(OAc) <sub>2</sub>	PCy <sub>3</sub>	K <sub>3</sub> PO <sub>4</sub> ·H <sub>2</sub> O	88
10	Pd(OAc) <sub>2</sub>	PCy <sub>3</sub> / PPh <sub>3</sub> <sup>c</sup>	K <sub>3</sub> PO <sub>4</sub>	67
11	Pd(OAc) <sub>2</sub>	PCy <sub>3</sub>	K <sub>2</sub> CO <sub>3</sub>	76
12	Pd (PPh <sub>3</sub> ) <sub>2</sub>	PPh <sub>3</sub>	K <sub>2</sub> CO <sub>3</sub>	20

<sup>a</sup> Reaction conditions : compound **173** (0. 77 mmol), bromobenzene (0.50 ml), Pd cat. (4 mol %), ligand (8 mol %), base (3 equiv.) and water (0.1 ml). Closed vessel, 80 Watts of microwave energy, 100 °C, 100 Psi of pressure, 10 minutes. <sup>b</sup> Isolated yields after column chromatography. <sup>c</sup> 4 mol% each of the ligands.

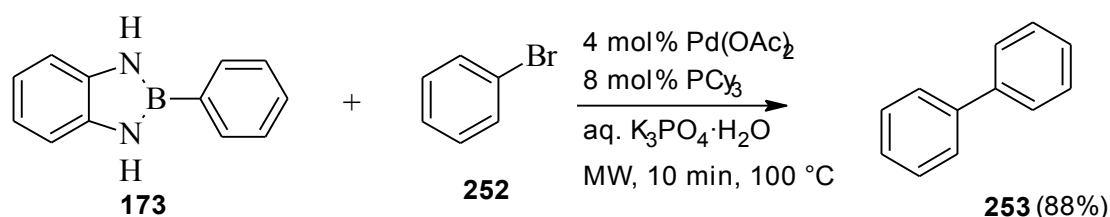
Attempted cross-coupling reaction of compound **173** with bromobenzene in the absence of both the ligand and base gave zero conversion of the starting materials (Table 1, entry 1). These results clearly suggested that the base and ligand are crucial

for the cross-coupling reaction in hand.<sup>17</sup> The addition of PPh<sub>3</sub> ligand and K<sub>3</sub>PO<sub>4</sub> base failed to afford any of the desired coupled-product in quantitative yields (Table 1, entry 2). Poor conversion of both starting material was also noted with the use of a bulky Pd(PPh<sub>3</sub>)<sub>4</sub> catalyst (Table 1, entries, 3 and 5). The use of Pd(PPh<sub>3</sub>)<sub>2</sub> catalyst in conjunction with PPh<sub>3</sub> ligand and K<sub>2</sub>CO<sub>3</sub> or K<sub>3</sub>PO<sub>4</sub>·H<sub>2</sub>O also failed to optimise the reaction conditions (Table 1, entries 4, 6 and 12). This observation was attributed to the decomposition of Pd(PPh<sub>3</sub>)<sub>2</sub> catalyst to Pd-black. Moderate to good yields (67%-88%) were obtained with the use of Pd(OAc)<sub>2</sub> and PCy<sub>3</sub> or the combination of PCy<sub>3</sub> and PPh<sub>3</sub> as supporting ligands (Table 1, entries 9-11). With the optimized reaction condition in hand {(Pd(OAc)<sub>2</sub> as catalyst, PCy<sub>3</sub> as supporting ligand, K<sub>3</sub>PO<sub>4</sub>·H<sub>2</sub>O as base and water}, several aryl bromides bearing either the electron-withdrawing or electron-donating substituents were reacted with 2-arylbenzo-1,3,2-diazaborolane compounds under the optimised reaction conditions.

The synthesis of asymmetrical biaryls under the optimal reaction conditions were conducted following two different approaches (A and B) depending on the physical state of the substrate. Liquid aryl bromides were coupled to 1,3,2-diazaborolane following general procedure A and the solid substrates were coupled *via* general procedure B.

#### 4.5.2.2 Representative Procedure for Solvent free Reactions (A)

##### 4.5.2.2.1 Synthesis of Biphenyl (253)

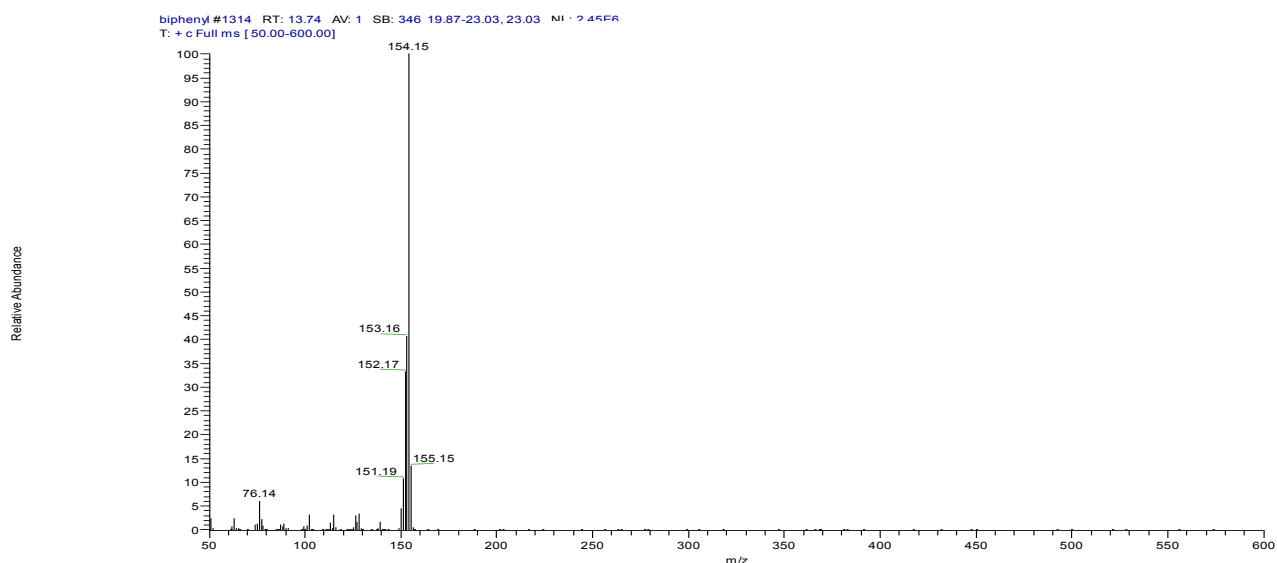


**Scheme 84**

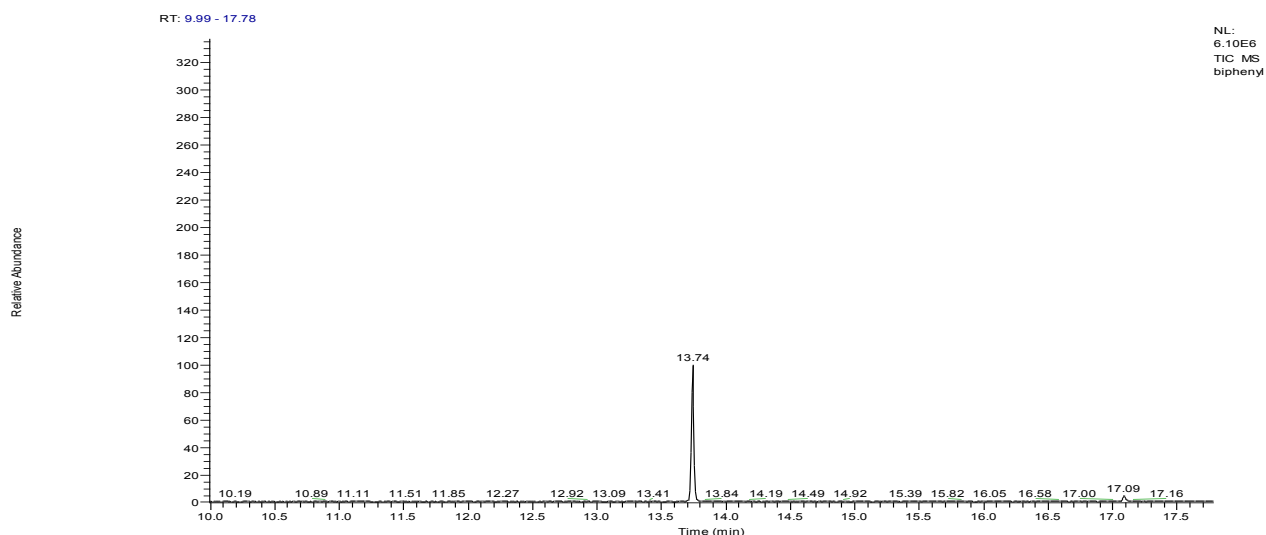
Biphenyl (**253**) was prepared in an isolated yield of 88% as a cream white solid from the reaction of 2-phenylbenzo-1,3,2-diazaborolane (**173**) and bromobenzene (**252**). The yield of the coupled product (**253**) obtained is comparable to the yield of 88% obtained by Chandrasekhar and co-workers<sup>87</sup> after refluxing the reaction mixture for more than 5 hours (**Scheme 84**). The structure and the purity of the product were



confirmed using spectroscopic techniques ( $^1\text{H}$ ,  $^{13}\text{C}$  NMR and GC-MS). The  $^1\text{H}$  NMR spectrum of the obtained cream white solid was consistent with the expected structure as evident with the integral ratios corresponding to the desired product (**253**). The purity of the product was also confirmed by GC-MS which showed one major peak with a retention time of 13.7 minutes corresponding to a molecular ion peak  $[\text{M}^+]$  with a molecular mass of  $154\text{ g.mol}^{-1}$  (**Figures 50 and 51**). The melting point of the desired product was found to be in the range of  $69\text{-}70\text{ }^\circ\text{C}$  which is similar to that reported by Zhang *et al.* of  $69\text{-}70\text{ }^\circ\text{C}$ .<sup>88</sup>



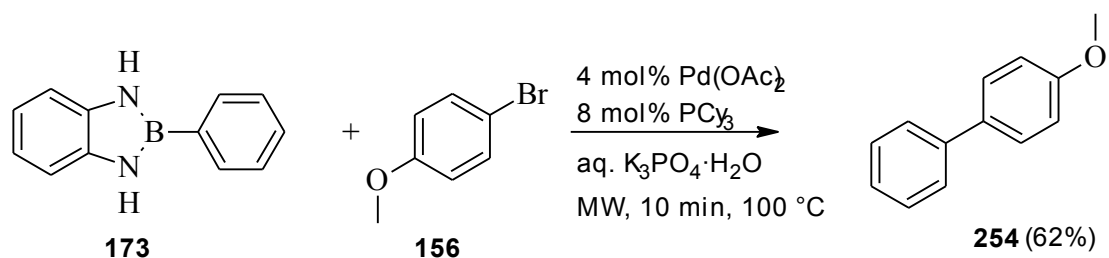
**Figure 50: GC spectrum for compound 253**



**Figure 51: GC trace for compound 253**

#### 4.5.2.2.2 Synthesis of 4-phenylanisole (254)

The preparation of 4-phenylanisole (**254**) was successfully achieved by the reaction of 2-phenylbenzo-1,3,2-diazaborolane (**173**) and 4-bromoanisole (**156**) following the general procedure A (Scheme 85). 4-Phenylanisole (**254**) was synthesised in 62%, a yield which is significantly higher than the yield reported by Bezier and co-workers (35%).<sup>89</sup>



Scheme 85

The <sup>1</sup>H NMR spectrum of the desired-product showed the integral ratios corresponding to the expected number of protons and the assignments are depicted in Figure 53. According to the COSY spectrum, the protons whose singlet resonates at δ 3.87 ppm was not coupled to any of the other protons and was assigned to the methoxy group. The doublet protons (with *J* = 8.9 Hz) are coupled to protons whose multiplet appears in the range δ 7.56-7.60 ppm. The former protons are assigned to 2-H and 6-H, and the latter to protons 2'-H, 6'-H, 5-H and 6-H. The triplet resonating at δ 7.43 ppm (*J* = 7.3 Hz) is coupled to a multiplet resonating in the range δ 7.32-7.38 ppm, these protons were assigned to protons 3'-H, 5'-H and 4'-H. The <sup>13</sup>C NMR spectrum of the desired product was similar to that obtained by Bezier and co-worker.<sup>89</sup> The title compound was obtained as a white solid which melts in the range of 92-93 °C which is in good agreement with the literature melting point of 90-91 °C.<sup>90</sup> The GC trace of the desired product showed a single peak with a retention time of 17.2 minutes corresponding to the expected molecular mass for C<sub>13</sub>H<sub>12</sub>O of 184. The infrared analysis showed a strong sharp band resonating at 1240 cm<sup>-1</sup> which corresponds to the O—CH<sub>3</sub> bond stretching frequency.

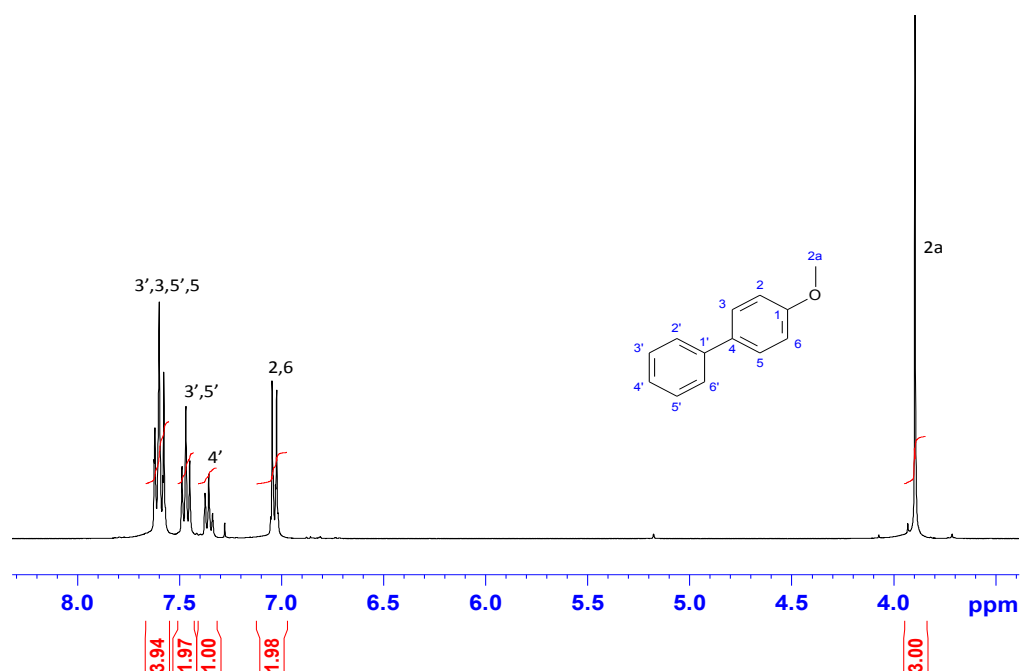
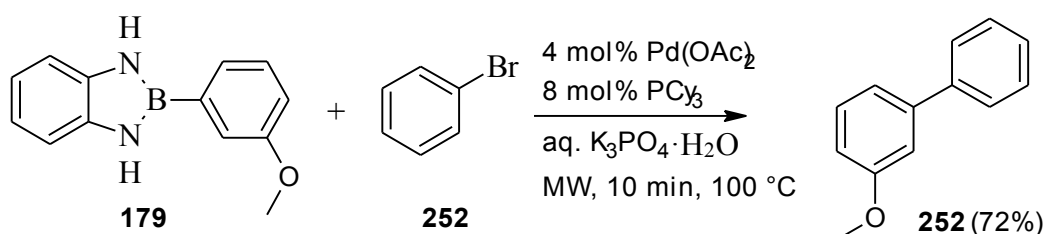


Figure 53:  $^1\text{H}$  NMR spectrum for compound 254.

#### 4.5.2.2.3 Synthesis of 3-phenylanisole (255)

With 2-(3-methoxyphenyl)-benzo-1,3,2-diazaborolane (**179**) in hand, 3-phenylanisole (**255**) could be successfully synthesised from the cross-coupling reaction of 2-(3-methoxyphenyl)-benzo-1,3,2-diazaborolane (**179**) with bromobenzene (**252**) as a clear oil in 72% isolated yield (Scheme 86).

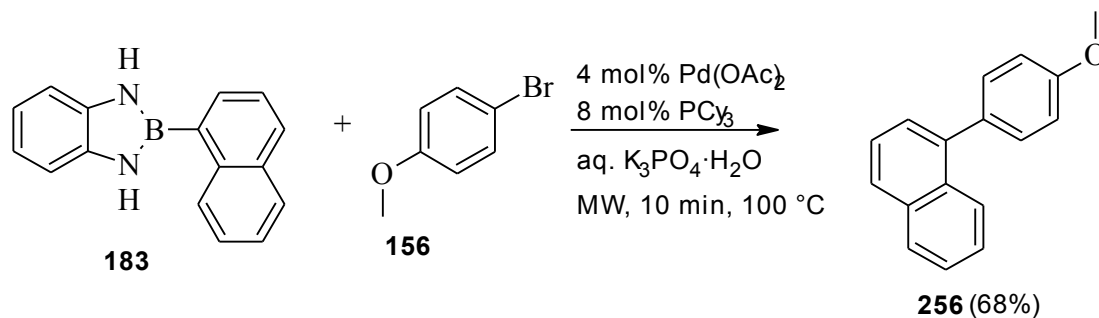


Scheme 86

The structure and the purity of the product were confirmed with spectroscopic data ( $^1\text{H}$ ,  $^{13}\text{C}$  NMR and GC-MS). The  $^1\text{H}$  NMR spectrum confirmed the existence of the product and revealed it to be clean as evident by the integral ratios corresponding to the expected number of protons expected in the desired product (**255**). The purity of the product was also confirmed with GC-MS which showed one major peak with a retention time of 16.9 minutes corresponding to the calculated molecular mass for  $\text{C}_{13}\text{H}_{12}\text{O}$  of 184.<sup>91</sup>

#### 4.5.2.2.4 Synthesis of 1-(4-methoxyphenyl)-naphthalene (256)

1-(4-Methoxyphenyl)-naphthalene (**256**) was synthesised in 68% isolated yield from the reaction of 2-(1-naphthalenyl)-benzo-1,3,2-diazaborolane (**183**) with 4-bromoanisole (**156**) (Scheme 87). The yield obtained compares favourably with the yield of 72% achieved by Quasdorf and co-workers after 24 hours of reflux.<sup>92</sup>



Scheme 87

The <sup>1</sup>H and <sup>13</sup>C NMR spectroscopic data of the obtained product are consistent with the anticipated structure and assignments are depicted in Figure 66 below. The title compound was obtained as white crystals which melts in the range of 116-117 °C and agrees favourably with the literature melting point of 116-117 °C.<sup>93</sup> A strong band at 1239 cm<sup>-1</sup> in the infrared spectrum of the desired-product confirmed the presence of a methoxy group, as it corresponds to O—CH<sub>3</sub> stretching vibration.

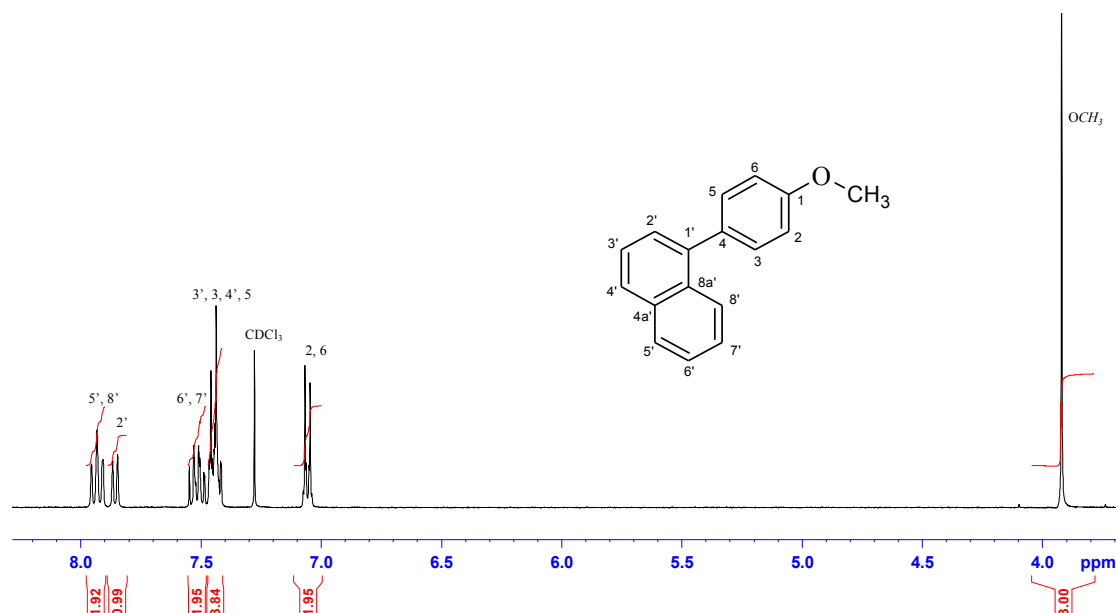
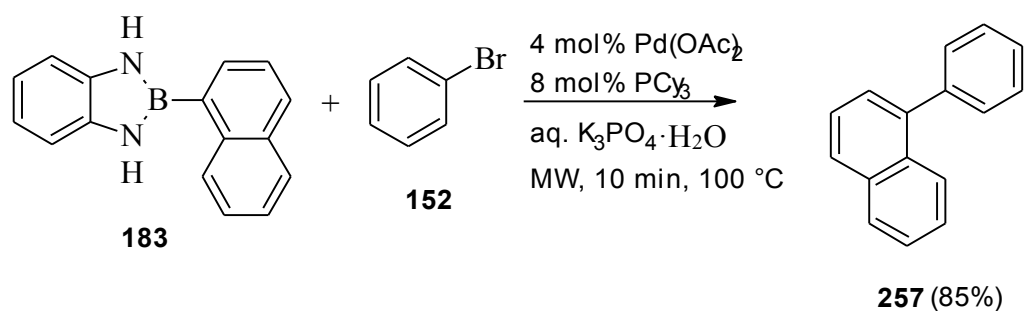


Figure 54: <sup>1</sup>H NMR spectra for compound **256**.

#### 4.5.2.2.5 Synthesis of 1-(phenyl)-naphthalene (257)

Bromobenzene (**252**) was reacted with 2-(1-naphthalenyl)-benzo-1,3,2-diazaborolane (**183**) to afford the title compound in a yield of 85% after isolation (**Scheme 88**). This yield is significantly higher than the 66% yield obtained by Chandrasekhar and co-workers<sup>94</sup> from the reaction of the corresponding boronic acid as a coupling partner.

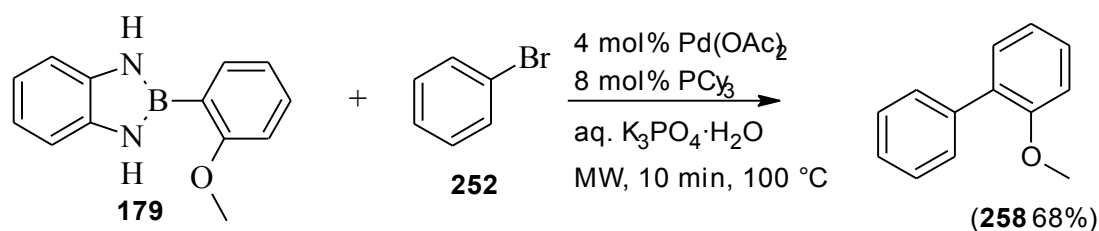


**Scheme 88**

The <sup>1</sup>H and <sup>13</sup>C NMR spectra of the desired product are in good agreement with that reported in literature. The product was obtained as clear oil, which is consistent with the finding of Qin and co-worker.<sup>95</sup>

#### 4.5.2.2.6 Synthesis of 2-phenylanisole (258)

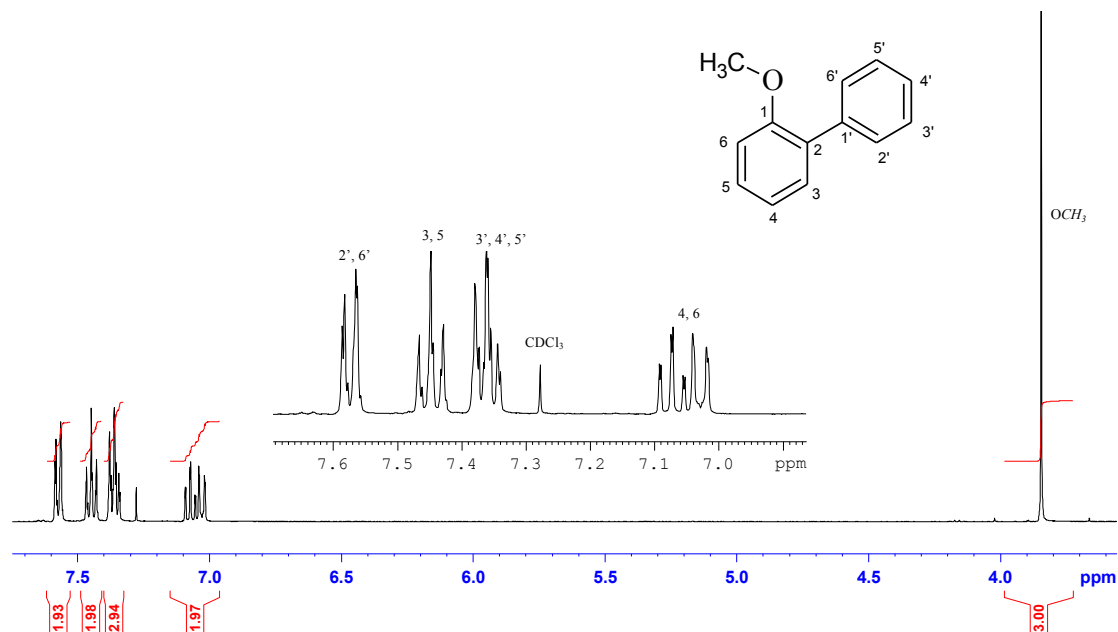
The synthesis of 2-phenylanisole (**258**) from 2-(2-methoxyphenyl)benzo-1,3,2-diazaborolane (**179**) as a coupling partner has proven more efficient than its synthesis from the corresponding boronic acid (**Scheme 89**).



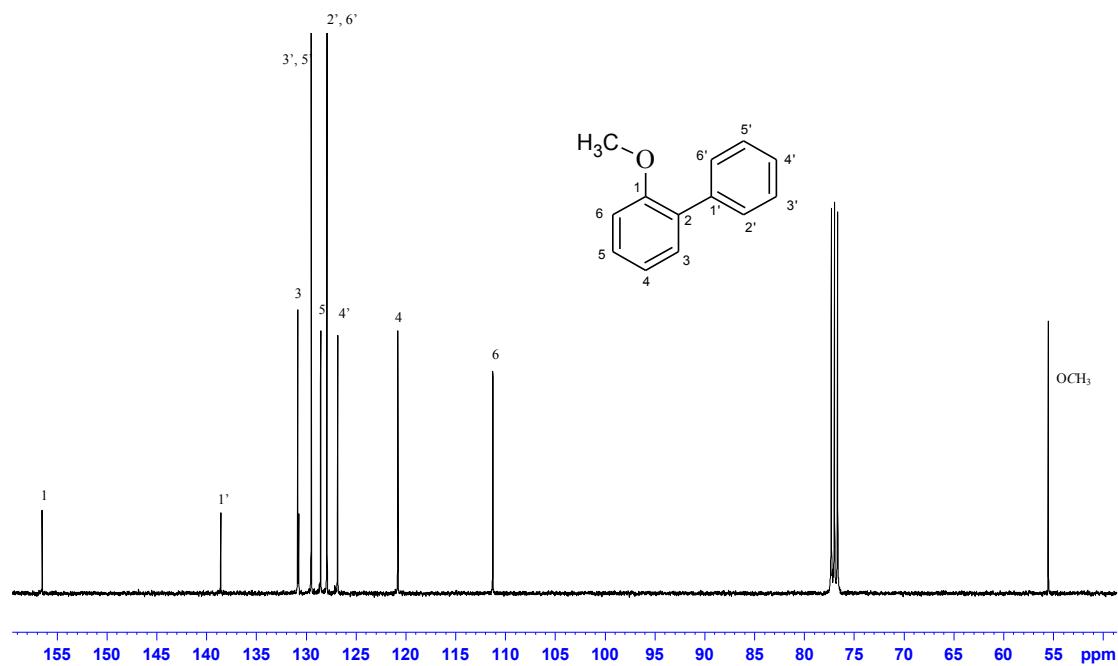
**Scheme 89**

2-Phenylanisole (**258**) was obtained in a yield of 68% which is higher than the 40% yield obtained when the corresponding boronic acid was used.<sup>96</sup> 2-Phenylanisole was obtained as a clear oil and this observation was supported by the findings of Wei and co-workers.<sup>97</sup> The GC-MS spectrum showed a peak with a relative abundance of 100%, this peak resonates at 184 which correspond to the molecular ion of the desired product.

The structure and the purity of the title compound was confirmed using  $^1\text{H}$  and  $^{13}\text{C}$  NMR spectroscopic data, and the assignments are depicted in **Figures 55** and **56** below.



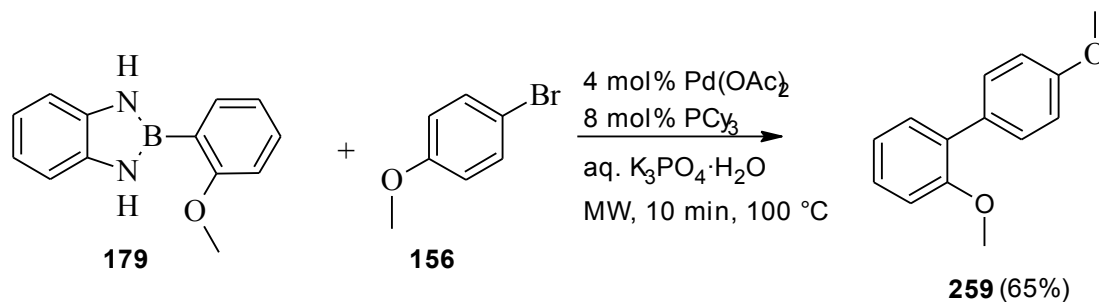
**Figure 55:  $^1\text{H}$  NMR spectrum for compound 258**



**Figure 56:  $^{13}\text{C}$  NMR spectrum for compound 258**

#### 4.5.2.2.7 Synthesis of 4-(2-methoxyphenyl)-anisole (259)

The title compound was synthesised in 65% from the cross coupling reaction between 2-(2-methoxyphenyl)-benzo-1,3,2-diazaborole (**179**) with 4-bromoanisole (**156**). The yield obtained from this coupling reaction is lower than the 98% yield reported by Lee and co-workers (**Scheme 90**).

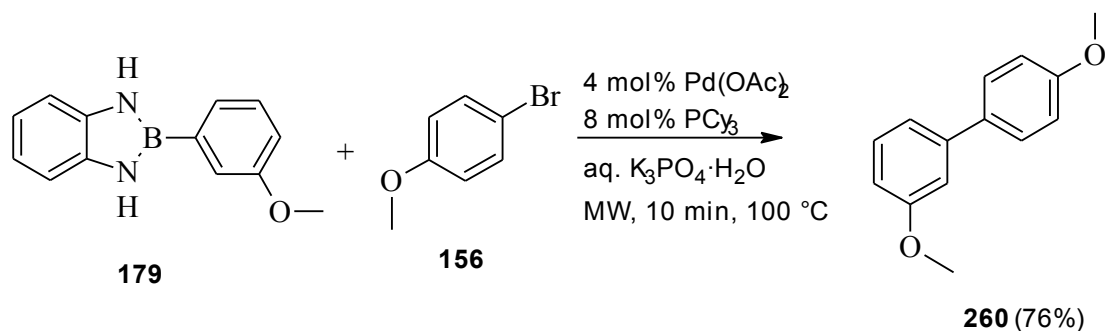


**Scheme 90**

The low yield obtained from this reaction was attributed to poor reactivity of **179** as evident by a large amount of this starting material recovered after the reaction as well as the formation of undesired products. These observations are supported by Marcuccio and co-workers<sup>98</sup> who also reported that organoborane compounds bearing electron-donating substituents are susceptible to homocoupling with the phosphine ligands, resulting in the formation of undesirable products.<sup>98</sup> Attempts to increase the reaction time to 20 minutes did not provide any improvements in overall yields of the reaction. The structure and the purity of the product were confirmed using <sup>1</sup>H and <sup>13</sup>C NMR spectra which proved to be consistent with the literature reports. The melting point of the desired product was recorded in the range of 69-70 °C which agrees favourably to the reported melting range of 69-70 °C.<sup>99</sup>

#### 4.5.2.2.8 Synthesis of 4-(3-methoxyphenyl)-anisole (260)

4-(3-Methoxyphenyl)-anisole (**260**) was furnished in 76% yield, after purification, when 2-(3-methoxyphenyl)-benzo-1,3,2-diazaborolane (**179**) was coupled to 4-bromoanisole (**156**) (**Scheme 91**).



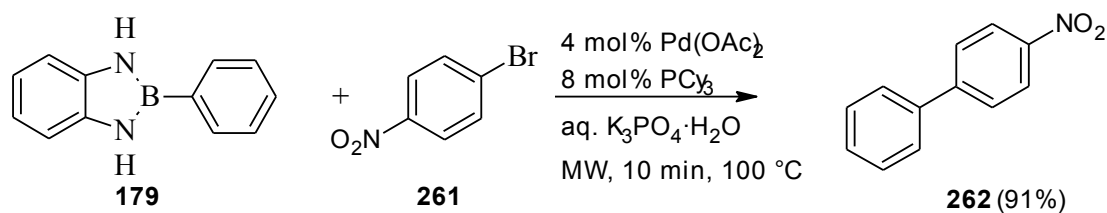
**Scheme 91**

The <sup>1</sup>H and <sup>13</sup>C NMR spectra are in good agreement with the expected structure and the GC trace confirmed the purity of the product as evidenced with a single major peak with a retention time of 16.9 minutes corresponding to the expected molar mass of 184. The melting point temperature was observed in the range of 56-57 °C which is consistent with the literature range of 58-59 °C reported by Itoh *et al.*<sup>100</sup>

#### 4.5.2.3 Representative Procedure for Solid Substrates

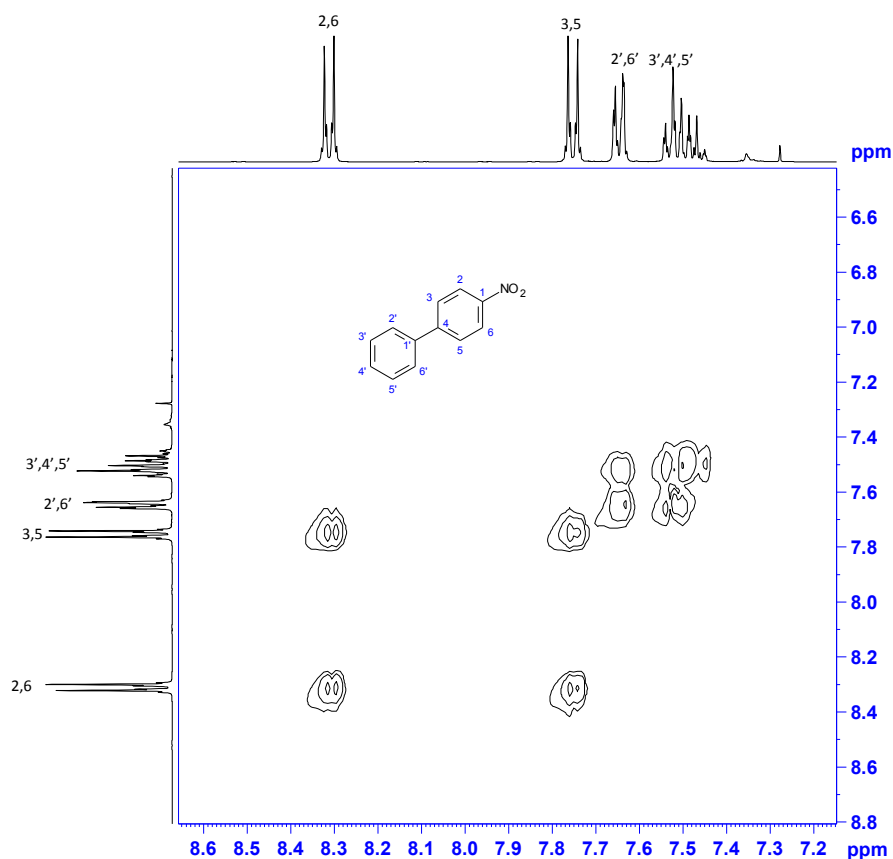
##### 4.5.2.3.1 Synthesis of 4-phenylnitrobenzene (262)

4-Phenylnitrobenzene (262) was successfully synthesised from the reaction of 4-bromonitrobenzene (261) with 2-phenylbenzo-1,3,2-diazaborolane (176) (**Scheme 112**). The product was obtained in an isolated yield of 91% which is higher than 86% yield obtained from the corresponding boronic acid as coupling partner reported by Schweizer *et al.*<sup>101</sup> The melting point of the product was recorded in the range of 112-114 °C and compares well with the literature value of 112-114°C.<sup>102</sup>



**Scheme 92**

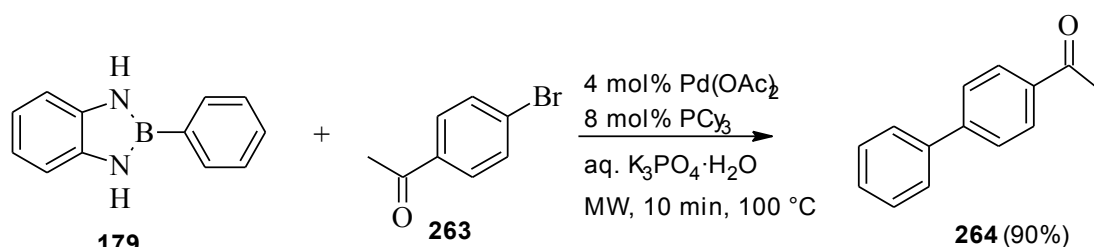




**Figure 57: COSY NMR spectrum for compound 262**

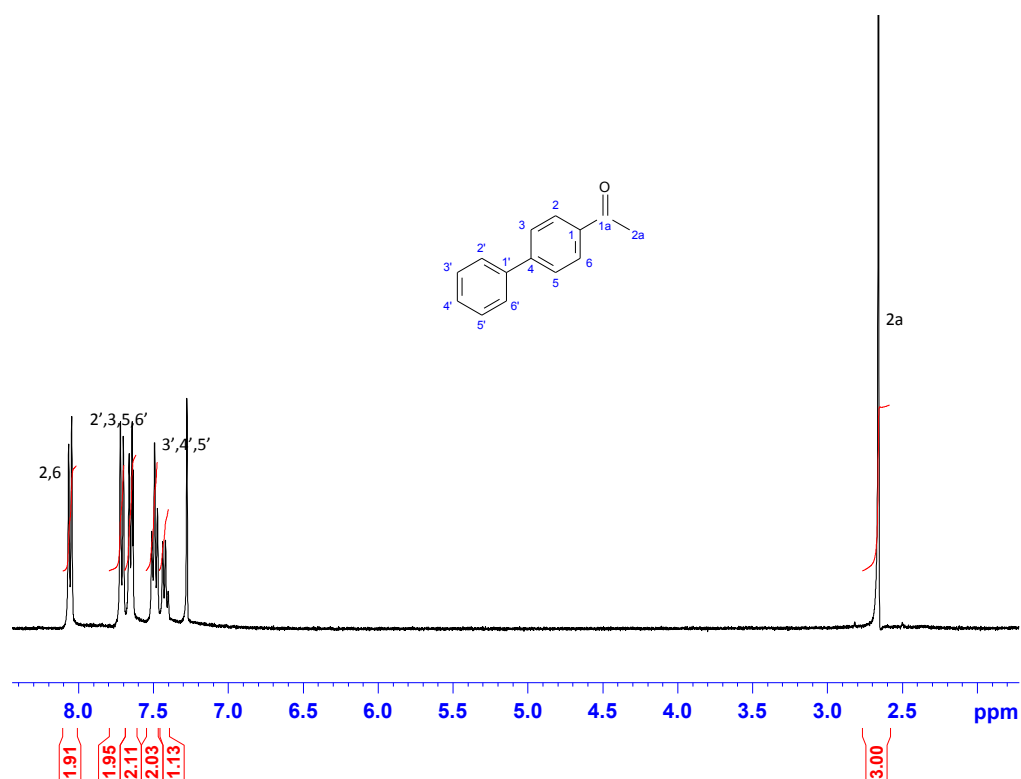
#### 4.5.2.3.2 Synthesis of 4-phenylacetophenone (264)

The cross-coupling reaction of 2-phenylbenzo-1,3,2-diazaborolane (**179**) with 4-bromoacetophenone (**263**) afforded 4-phenylacetophenone (**264**) in 90% isolated yield in 10 minutes (**113**). The yield of the coupled product (**264**) obtained is higher than 85% yield achieved by Chandrasekhar and co-workers<sup>94</sup> using boronic acid as the coupling partner after heating the mixture under reflux for 10 hours.



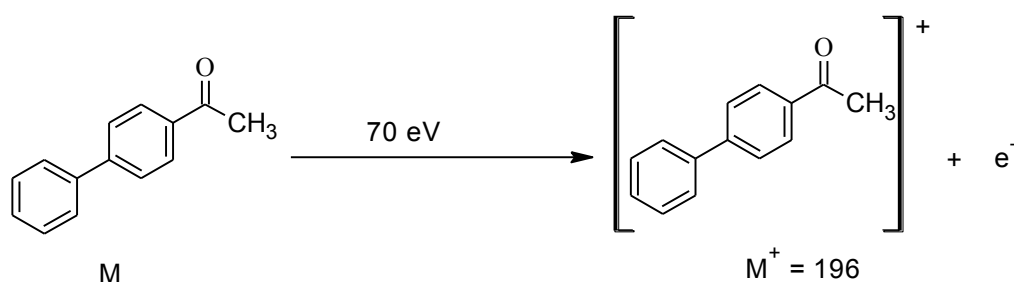
**Scheme 93**

To confirm the structure of the product, the <sup>1</sup>H NMR spectrum of the product was acquired and it revealed the expected peaks with the integral ratios exactly matching the number of protons (**Figure 58**).



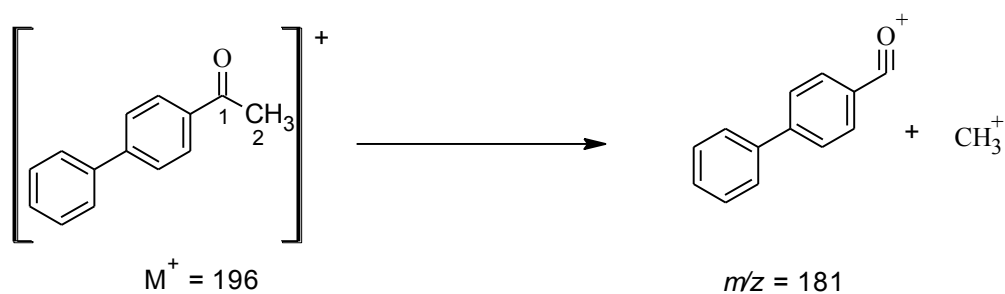
**Figure 58:**  $^1\text{H}$  NMR spectra for compound **264**

GC-MS (**Figure 59**) showed a molecular ion peak  $[\text{M}^+]$  with an  $m/z$  value of 196 g. mol $^{-1}$  which results when **264** is bombarded with a beam of high-energy electron such that it loses an electron and becomes positively charged (**Scheme 94**)

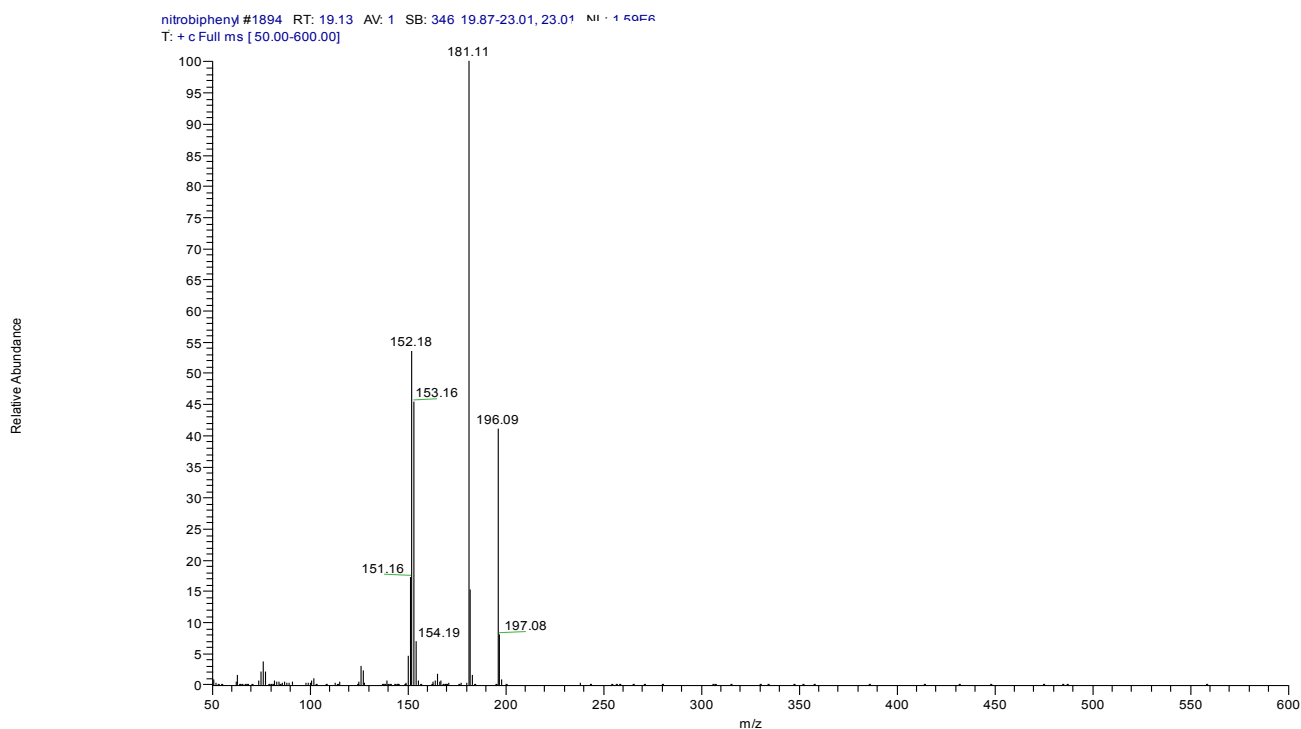


**Scheme 94**

The base peak with an  $m/z$  value of 181 mass units is due to a  $\text{C}_1\text{--C}_2$  fragmentation. The cleavage of this bond leads to the formation of stable fragment ions ( $\text{C}_{13}\text{H}_9\text{O}^+$ ) and  $\text{CH}_3^+$  with the former ion having a relative abundance of 100% (**Scheme 95**).



**Scheme 95**



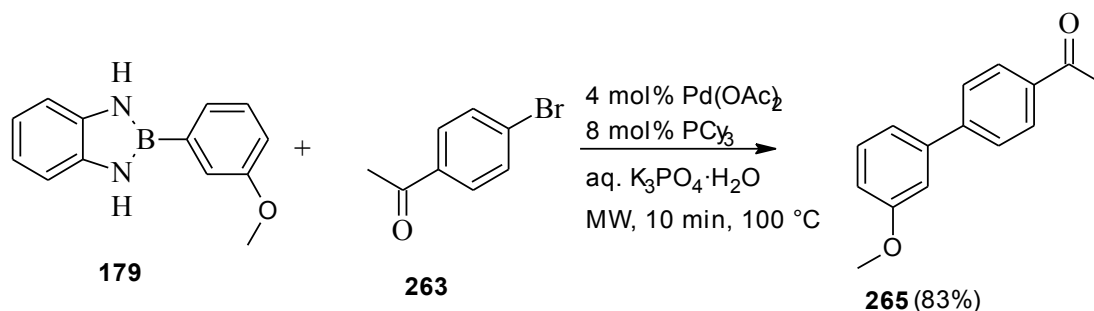
**Figure 59: GC spectrum for compound 246**

The infrared spectrum of the product confirmed the presence of the carbonyl functionality as evident with a broad absorption band at  $1675\text{ cm}^{-1}$  corresponding to the stretching vibration of C=O bond. The melting point of the product was found to be in the range  $120\text{-}124\text{ }^{\circ}\text{C}$  which is consistent with the reported melting point of  $122\text{-}124\text{ }^{\circ}\text{C}$ .<sup>103</sup> The  $^{13}\text{C}$  NMR spectrum is also consistent with the anticipated structure as evident by ten carbons peaks as expected.

#### 4.5.2.3.3 Synthesis of 4-(3-methoxyphenyl)-acetophenone (265)

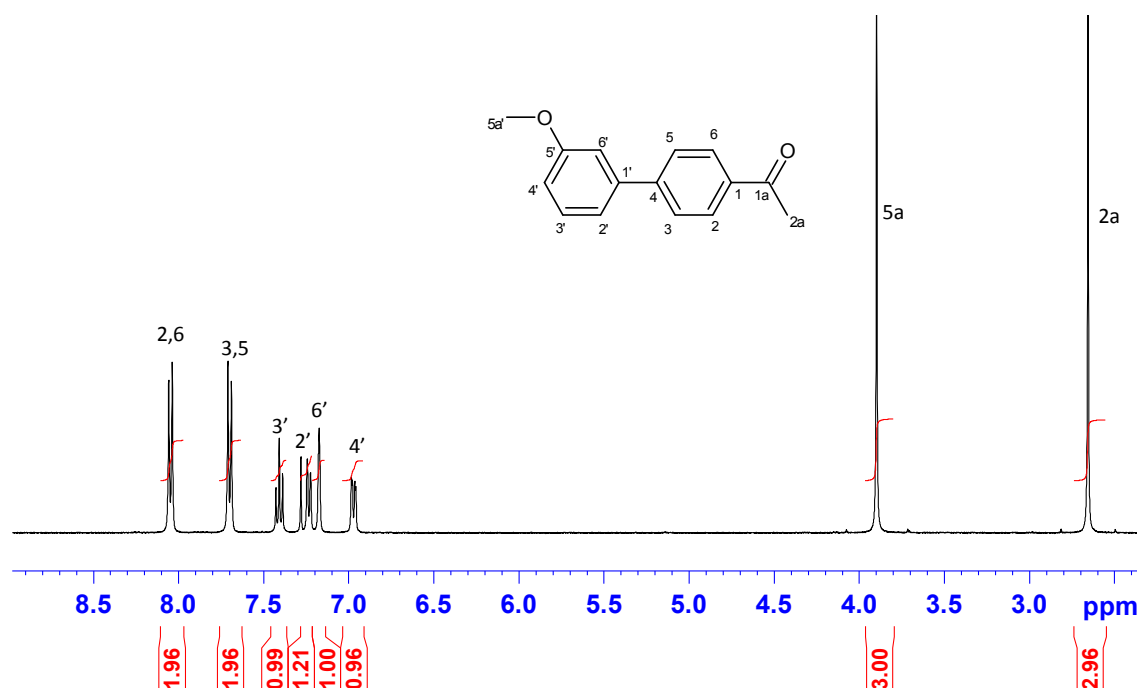
The cross coupling reaction of 2-(3-methoxyphenyl)-benzo-1,3,2-diazaborolane (**180**) with 4-bromoacetophenone (**263**) afforded 2-(3-methoxyphenyl)acetophenone (**265**) in 83% isolated yield (**Scheme 116**). Our yield is higher than the 36% and 77% yields

achieved by Saito *et al.*<sup>104</sup> when they used the corresponding boronic acid as coupling partner. The <sup>1</sup>H NMR spectrum of the product revealed the product to be clean and is consistent with the predicted spectrum (**Figure 59**).



**Scheme 96**

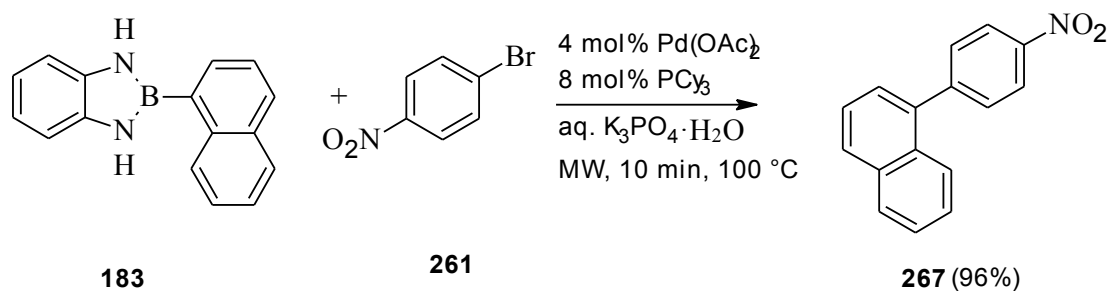
GC-MS trace of the product showed a peak with a retention time of 21.7 minutes, corresponding to calculated molecular mass for C<sub>15</sub>H<sub>14</sub>O<sub>2</sub> of 226. The infrared spectrum of the product confirmed the presence of a carbonyl functionality as evident by the characteristic absorption band at 1670 cm<sup>-1</sup> which corresponds to the C=O stretching vibration. The purity of the product was also confirmed by the melting point temperature, which was found to be in the range of 88-90 °C, and matches exactly the range reported in the literature.<sup>91</sup>



**Figure 60:** <sup>1</sup>H NMR spectrum for compound 265.

#### 4.5.2.3.4 Synthesis of 1-(4-nitrophenyl)-naphthalene (267)

1-(4-Nitrophenyl)-naphthalene (**267**) was prepared in 96% isolated yield as a cream white solid from the reaction of 2-(1-naphthalenyl)benzo-1,3,2-diazaborole (**185**) and 4-bromonitrobenzene (**261**) (**Scheme 97**). The 96% yield obtained compares favourably with 91% yield reported in literature after heating the reaction mixture for 1.5 hours.

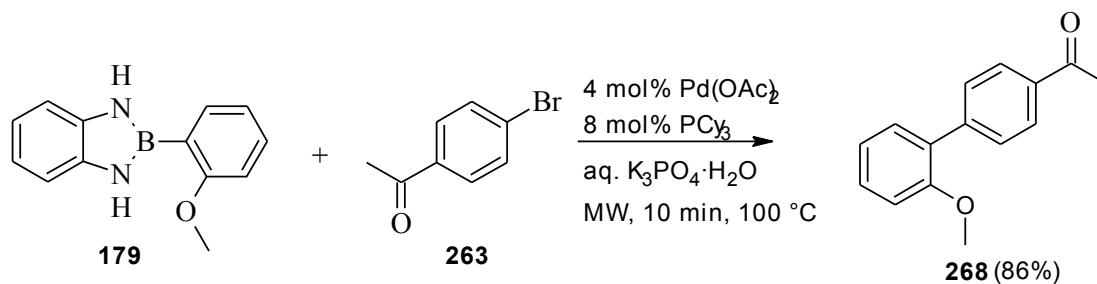


**Scheme 97**

The structure and the purity of the product were confirmed by spectroscopic data ( $^1\text{H}$ ,  $^{13}\text{C}$  NMR and GC-MS). The  $^1\text{H}$  NMR spectrum confirmed the existence of the product and revealed it to be relatively clean as evident by the integral ratios corresponding to the desired product (**268**). The GC-MS showed one major peak at a retention time of 20.2 minutes corresponding to the calculated mass for  $\text{C}_{16}\text{H}_{14}\text{NO}_2$  of 249. The melting point of the title compound was found to be 132-133 °C which matches exactly the melting range reported by Qin and co-workers.<sup>95</sup>

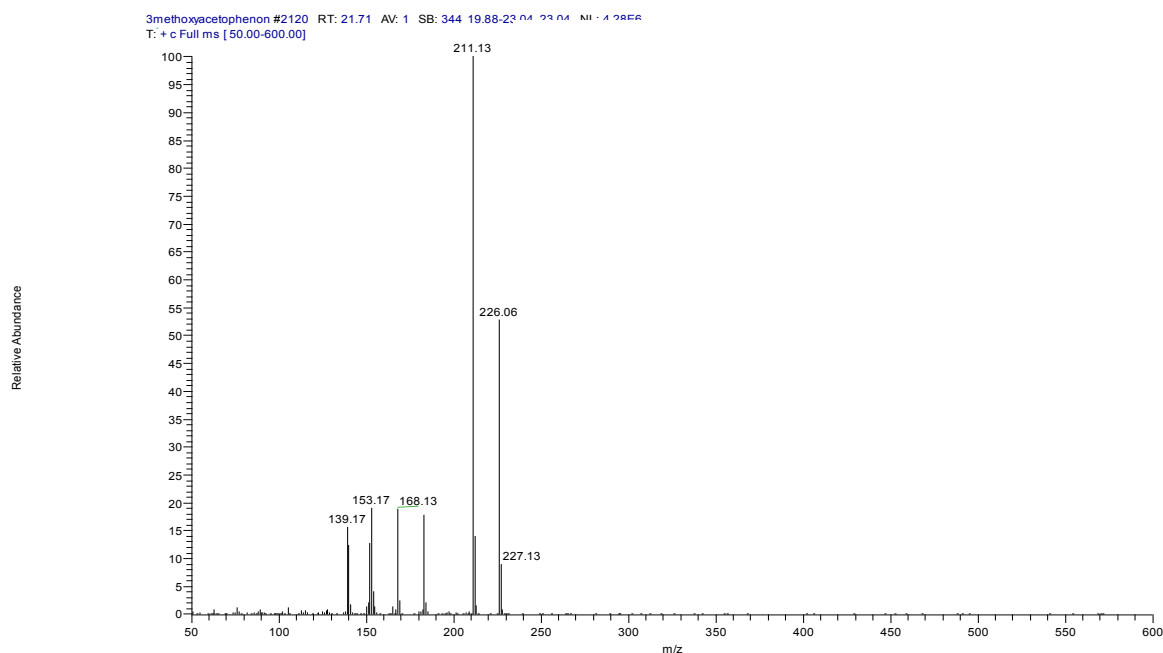
#### 4.5.2.3.5 Synthesis of 4-(2-methoxyphenyl)-acetophenone (268)

2-(2-Methoxyphenyl)-benzo-1,3,2-diazaborole (**179**) was coupled successfully with 4-bromoacetophenone (**263**) to afford 2-(methoxyphenyl)-acetophenone (**268**) in 86% isolated yield (**Scheme 98**). The yield of the desired product obtained is higher than the 65% yield achieved by Kelvin *et al.* when they used arylpinacolborate esters as the coupling partners.



**Scheme 98**

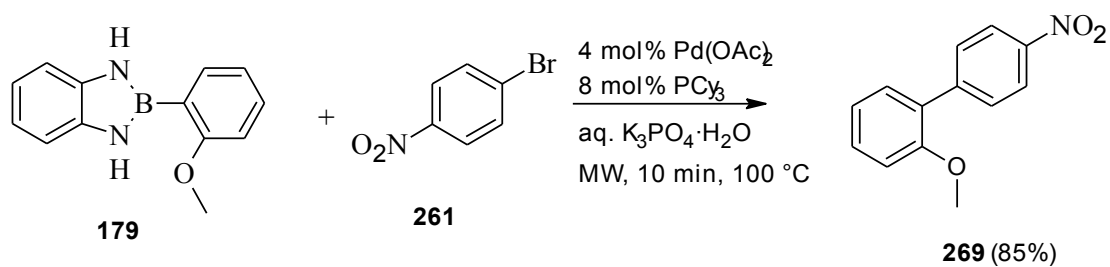
The  $^1\text{H}$  and  $^{13}\text{C}$  NMR spectra were used to assess the purity and confirm the structure of the product. Careful assignment of both the  $^1\text{H}$  and  $^{13}\text{C}$  NMR spectra revealed the expected product to be clean. The melting point temperature of the coupled product **268** was registered at 105-107°C which is in good agreement with the literature value of 105-106°C.<sup>105</sup> The GC-MS spectrum of the product showed a base peak with an  $m/z$  value of 211 mass units corresponding to the fragment ion ( $\text{C}_{14}\text{H}_{11}\text{O}_2^+$ ) (**Figure 61**). The peak with the relative abundance of *ca.* 55% corresponds to the molecular ion as it has an  $m/z$  value of 226 matching the calculated molar mass for  $\text{C}_{15}\text{H}_{12}\text{O}_2$  of 226. The infrared spectrum showed the presence of a sharp absorption bands at 1239  $\text{cm}^{-1}$  and 1670  $\text{cm}^{-1}$  corresponding to the stretching vibrations of the O—CH<sub>3</sub> and C=O bonds, respectively.



**Figure 61: GC spectrum for compound 268**

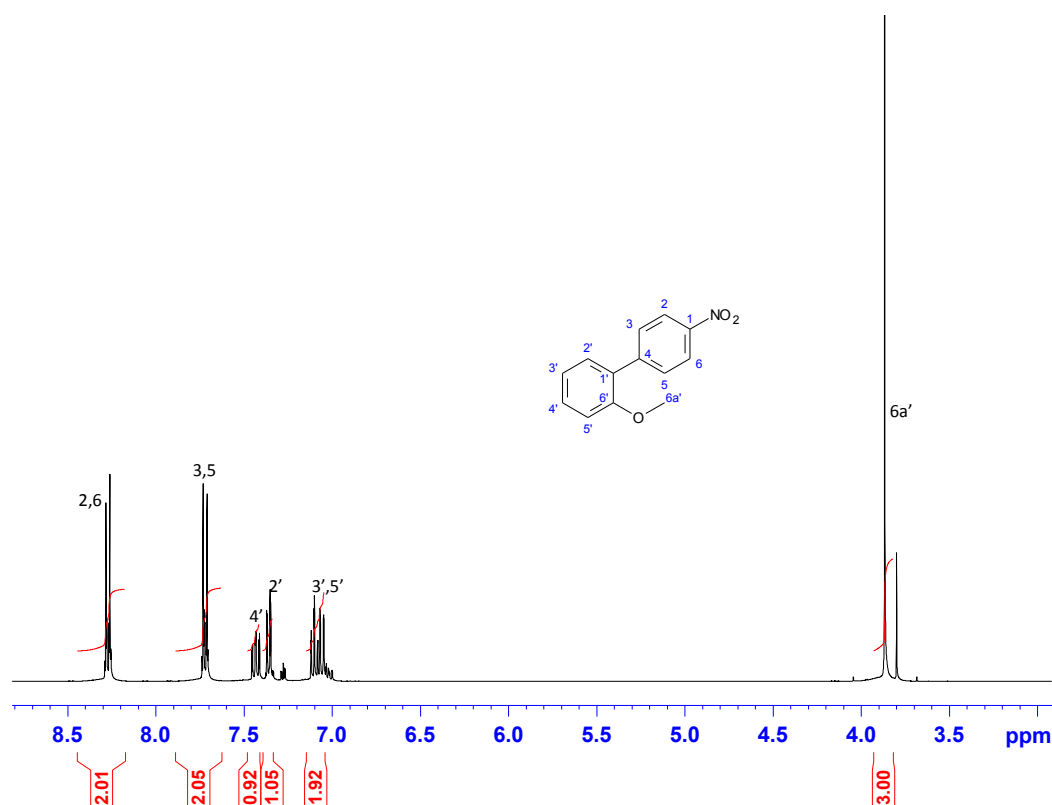
#### 4.5.2.3.6 Synthesis of 4-(2-methoxyphenyl)-nitrobenzene (**269**)

The cross-coupling reaction of 2-(2-methoxyphenyl)-benzo-1,3,2-diazaborolane (**179**) with 4-bromonitrobenzene (**261**) afforded 2-(methoxyphenyl)-nitrobenzene (**269**) in 85% yield based on NMR (**Scheme 99**). Purification of the title compound has proven laborious because the starting material (**179**) had a retention factor similar to that of the product.



### Scheme 99

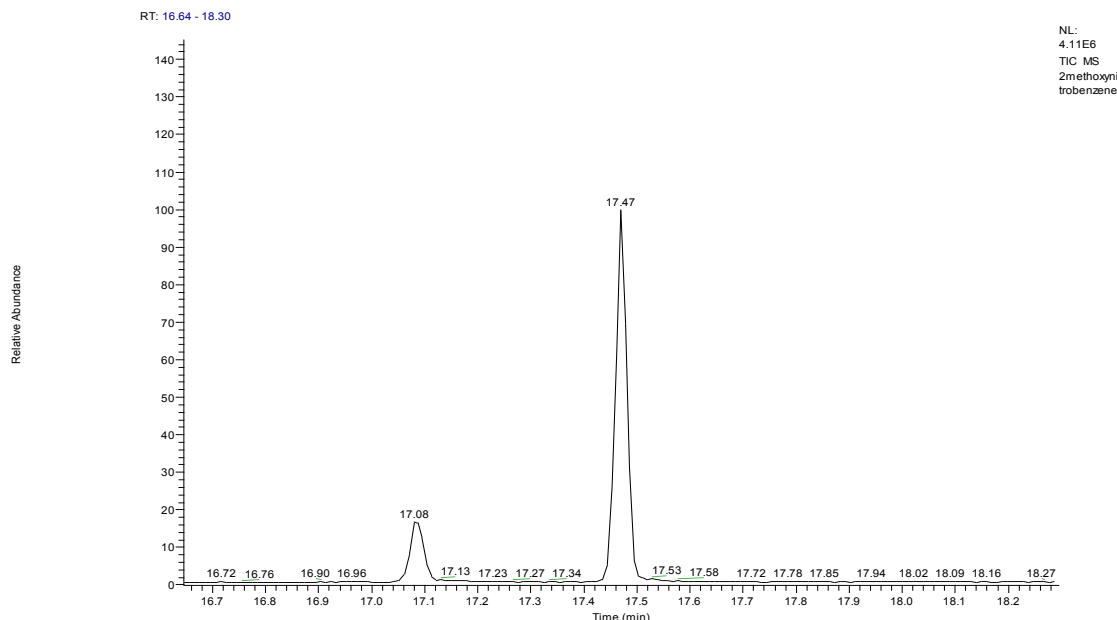
Attempted purification of the product using two consecutive radial chromatography discs was not successful. For this reason, it was difficult to remove the starting material and as a consequence, the yield of the desired product was based on the integration ratio of the  $^1\text{H}$  NMR. Despite the contamination of the desired product with the starting material, the  $^1\text{H}$  NMR spectrum revealed the product to be sufficiently clean and the assignments are consistent with the anticipated structure (**Figure 62**). It was, however, surprising to note that the melting point of the product was found in the range of 61-63°C which is similar to the range reported in literature,<sup>95</sup> despite the presence of the contamination.



**Figure 62:**  $^1\text{H}$  NMR spectrum for compound **269**.

As expected, the GC trace for the product (**Figure 63**) showed two peaks with a retention time of 17.08 minutes attributable to the starting material and the major peak

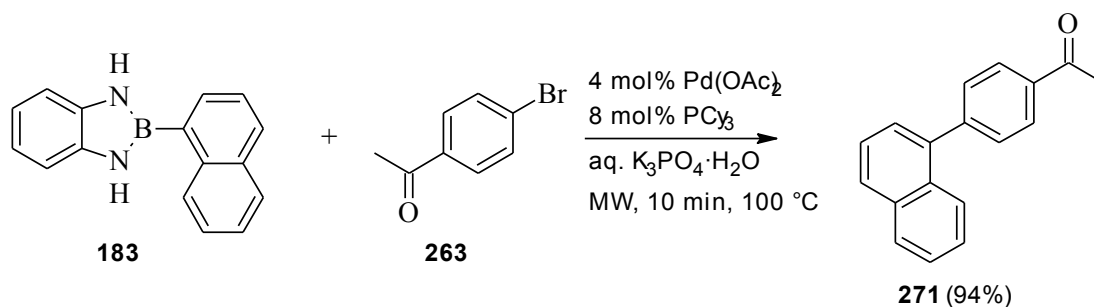
with a retention time of 17.47 minutes corresponding to the Suzuki coupled-product **269** (Figure 63). The infrared spectrum of the product shows the absorption bands at  $1231\text{ cm}^{-1}$  and  $1509\text{ cm}^{-1}$  which can be related to the stretching vibrations of the O-CH<sub>3</sub> and N-O bonds.



**Figure 63: GC trace for compound 269**

#### 4.5.2.3.7 Synthesis of 1-[4-(1-naphthalenyl)]-ethanone (270)

2-(1-Naphthalenyl)-benzo-1,3,2-diazaborolane (**183**) was successfully coupled with 4-bromoacetophenone (**263**) to afford the desired coupled-product (**270**) in an isolated yield of 94% (Scheme 100). To confirm the structure of the product, spectroscopic data was collected and carefully analysed.



**Scheme 100**

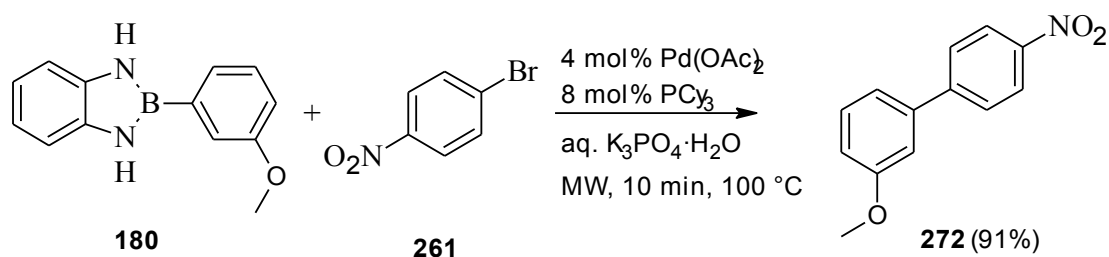
The <sup>1</sup>H NMR spectrum revealed the product to be clean as evident by the integral ratios corresponding to the expected number of protons. The purity of the coupled product was also reflected by the melting point of 102-103°C which is similar to melting point of 102-103°C reported in literature.<sup>95</sup> GC-MS analysis showed a peak



with a relative abundance of 100% which has a  $m/z$  value of 231 corresponding to the formation of  $[C_{17}H_{11}O]^+$  ion as a result of the fragmentation of the C–C bond adjacent to the carbonyl group. The infrared spectrum confirmed the presence of the carbonyl functionality as evident with the appearance of an absorption band at  $1681\text{ cm}^{-1}$  which corresponds to the stretching vibration of the C=O bond.

#### 4.5.2.3.8 Synthesis of 4-(3-methoxyphenyl)-nitrobenzene (272)

4-(3-Methoxyphenyl)-nitrobenzene (**272**) was achieved in an excellent 91% yield when 2-(3-methoxybiphenyl)-benzo-1,3,2-diazaborolane (**180**) was coupled with 4-bromonitrobenzene (**261**) under the optimised reaction conditions as described above (Scheme 101).

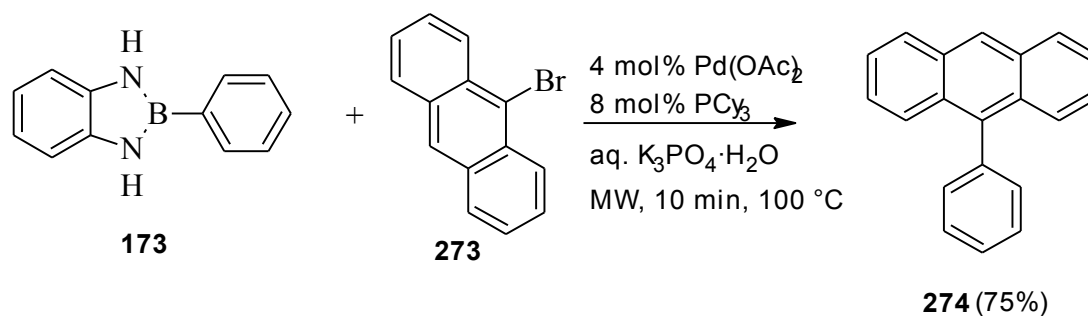


**Scheme 101**

The  $^1\text{H}$  and  $^{13}\text{C}$  NMR spectra were carried out and assigned accordingly. GC-MS analysis showed a peak with natural abundance of 100% corresponding to the molecular mass of 229 as expected for the desired product. The product was obtained as a white amorphous powder.<sup>99</sup>

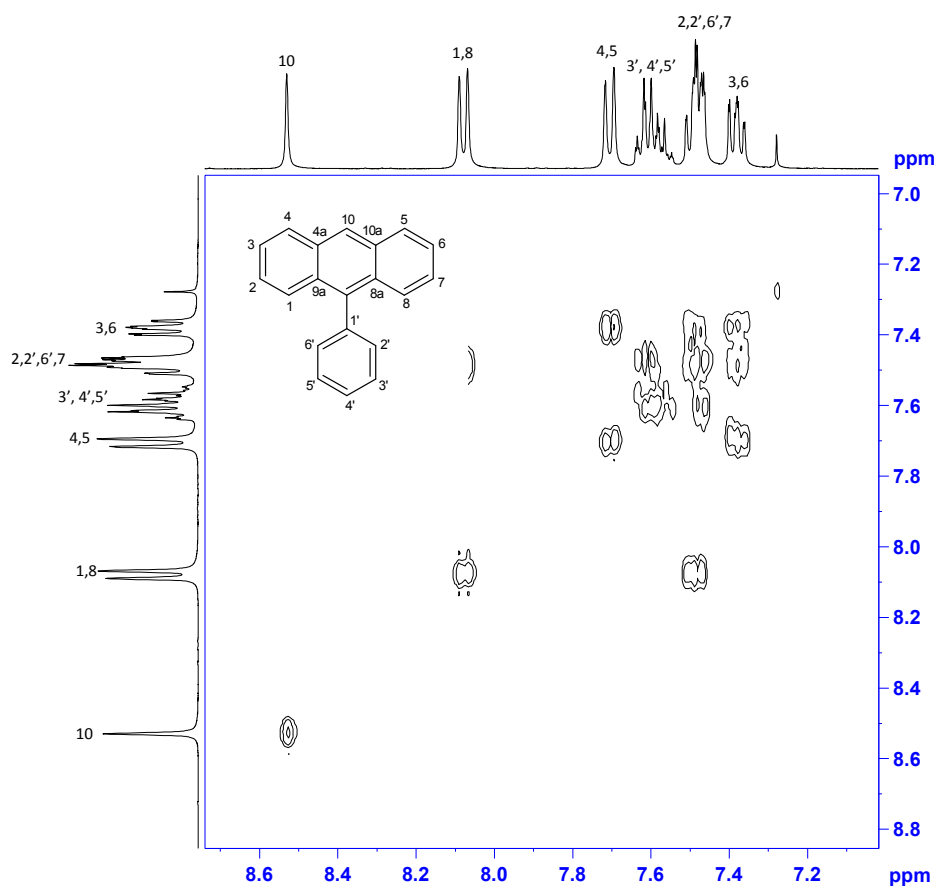
#### 4.5.2.3.9 Synthesis of 9-phenylanthracene (273)

The cross-coupling reaction between 2-phenylbenzo-1,3,2-diazaborole (**173**) with 9-bromoanthracene (**273**) mediated by  $\text{Pd}(\text{OAc})_2/\text{PCy}_3$  combination under the representative procedure B furnished the title product, after purification through silica gel, as colourless plates-like crystals in 75% yield (Scheme 102).



**Scheme 102**

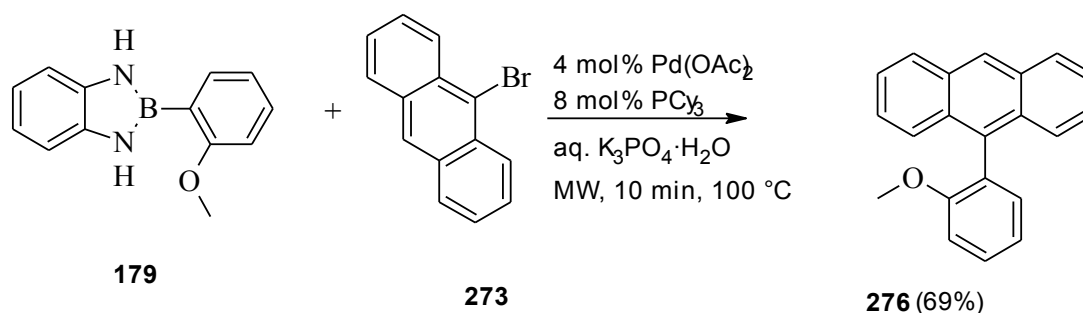
The COSY spectrum of the title compound displayed six different protons as illustrated on figure 75 below. The melting point was found in the range 155-157 °C which is close to the reported melting point range of 153-155 °C.<sup>106</sup>



**Figure 64: COSY spectrum for compound 274**

#### 4.5.2.3.10 Synthesis of 9-(2-methoxyphenyl)-anthracene (275)

2-(Methoxyphenyl)-benzo-1,3,2-diazaborole (**179**) was smoothly coupled with 9-bromonanthracene (**273**) as an electrophilic coupling partner to afford the coupled-product **275** in 72% yield following representative procedure B. After purifying the crude product, the desired product was obtained as cream-white amorphous powder whose <sup>1</sup>H and <sup>13</sup>C NMR spectra revealed the expected proton and carbon peaks which are consistent with anticipated structure.

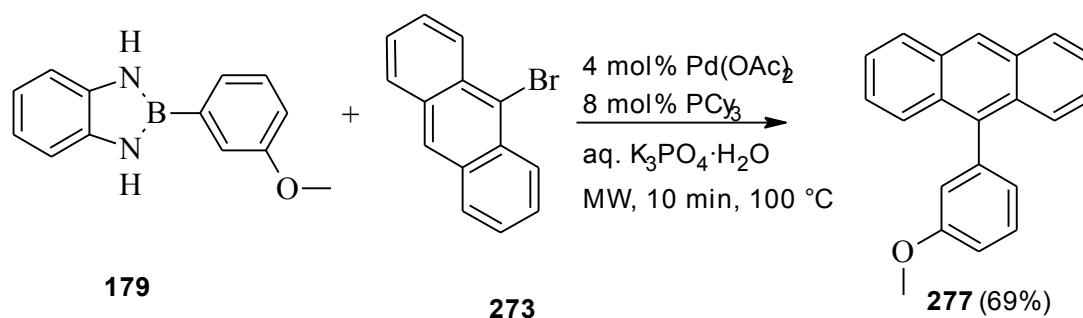


**Scheme 103**

GC-MS also confirmed the product as evident by the molecular peak  $[\text{M}^+]$  at 284 which is consistent with the calculated molar mass of the product. The melting point was found in the range of 177-178 °C (lit.<sup>107</sup>: 177-179 °C).

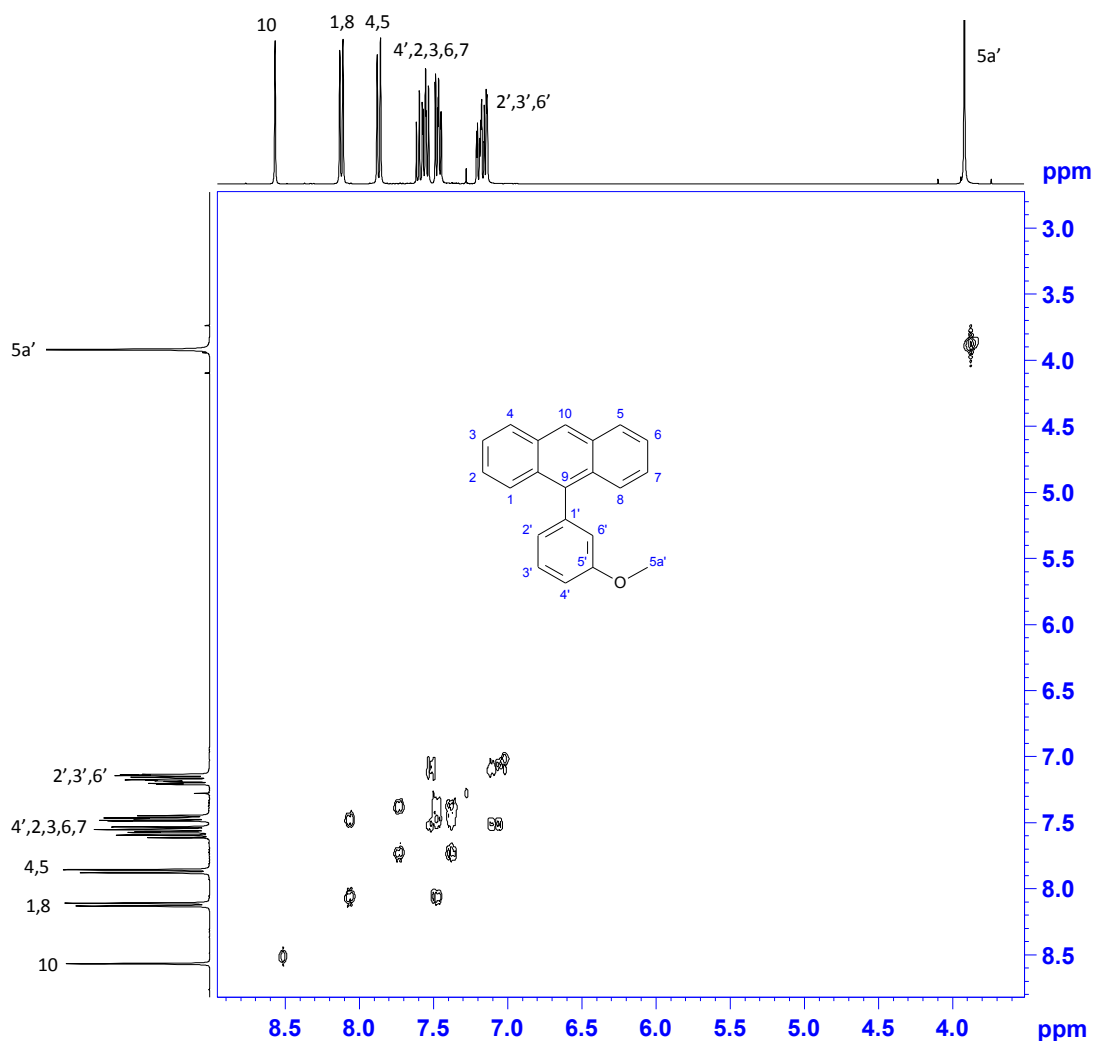
#### 4.5.2.3.11 Synthesis of 9-(3-methoxyphenyl)-anthracene (277)

9-Bromoanthracene (**273**) was successfully coupled with 2-(3-methoxyphenyl)-benzo-1,3,2-diazaborole (**180**) following the representative procedure B. The title compound was obtained as colourless crystals in 69% after the purification of the crude product (**Scheme 104**).



**Scheme 104**

The  $^1\text{H}$  and  $^{13}\text{C}$  NMR spectra of the obtained crystals are consistent with the anticipated structure confirming the successful preparation of **277**. The COSY spectrum for the title compound was also consistent with the anticipated structure and is depicted in figure 4.12. The melting point of the crystals was recorded in the range of 99-101 °C (lit.<sup>108</sup>: 99-100 °C).



**Figure 65. COSY spectrum for compound 277.**

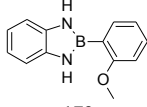

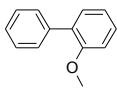
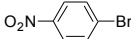
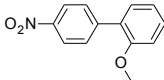

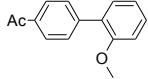
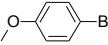
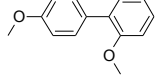
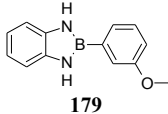
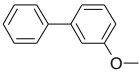
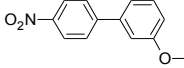
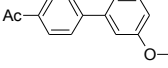
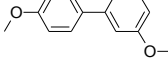
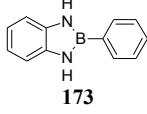
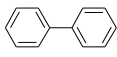
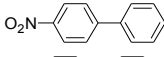
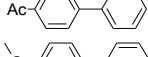
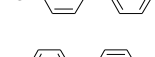
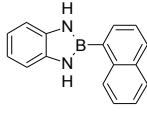
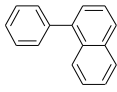
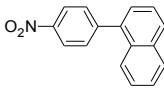
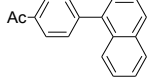
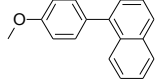
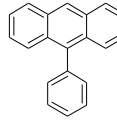
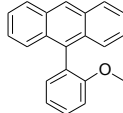
The COSY spectrum showed seven different resonances (**Figure 65**). The single integrating for three protons at  $\delta$  3.92 ppm was assigned to the methoxy group. The multiplet integrating for three protons whose signal appears in the range  $\delta$  7.13-7.21 ppm were assigned to protons 2'-H, 3'-H and 6'-H. The multiplets in the close range of  $\delta$  7.33-7.41 ppm and  $\delta$  7.44-7.55 ppm were assigned to 2-H, 3-H, 4'-H, 6-H and 7-H. The doublets resonating at  $\delta$  7.73 ppm and  $\delta$  8.06 ppm were assigned to protons 4-H, 5-H and 1-H, 8-H, respectively (**Figure 65**).

### **4.5.3 Summary of the Suzuki-Miyaura Cross-Coupling Reaction.**

In this section, the synthesised 2-arylbenzo-1,3,2-diazaborolane compounds were evaluated as potential Suzuki coupling partners. A range of aryl bromides bearing both electron-withdrawing and donating substituent were coupled with 2-arylbenzo-1,3,2-diazaborolane compounds under optimised reaction conditions to afford the substituted biphenyls in isolated yields ranging from 62-96% in only 10 minutes (**Table 4.2**).

The yields of substituted biphenyl products obtained in this project were compared with those achieved from the use of boronic acids as coupling partners and in most cases were shown to be significantly superior. 2-Arylbenzo-1,3,2-diazaborolane derivatives seems to be better Suzuki coupling partners than the boronic acids counterparts.

**Table 4.2.** Summary of Palladium-Catalyzed Suzuki-Miyaura Cross-Coupling Reaction.

Entry	diazaborolane	aryl bromide	conditions	product	% Yields
1	 <b>179</b>	 <b>252</b>	<b>A</b>		68
2		 <b>261</b>	<b>B</b>		85
3		 <b>263</b>	<b>B</b>		86
4		 <b>156</b>	<b>A</b>		65
5	 <b>179</b>	<b>252</b>	<b>A</b>		72
6		<b>261</b>	<b>B</b>		91
7		<b>263</b>	<b>B</b>		83
8		<b>156</b>	<b>A</b>		76
9	 <b>173</b>	<b>252</b>	<b>A</b>		88
10		<b>261</b>	<b>B</b>		91
11		<b>263</b>	<b>B</b>		90
12		<b>156</b>	<b>A</b>		62
13	 <b>183</b>	<b>252</b>	<b>A</b>		85
14		<b>261</b>	<b>B</b>		96
15		<b>263</b>	<b>B</b>		94
16		<b>156</b>	<b>A</b>		68
17	<b>173</b>	<b>273</b>	<b>B</b>		75
18	<b>179</b>	<b>273</b>	<b>B</b>		72

#### 4.5.4 Conclusion

A range of 2-arylbenzo-1,3,2-diazaborolane compounds were synthesised from the cyclocondensation of boronic acids with 1,2-diaminobenzene in isolated yields ranging from 71 to 98%.

With 2-arylbenzo-1,3,2-diazaborolane compounds in hand, their efficiency and versatility as Suzuki coupling partners were evaluated. The coupling reaction between 2-phenylbenzo-1,3,2-diazaborolane and bromobenzene was conducted under different palladium catalysts in order to optimise the reaction conditions. The optimal conditions were shown to be the combination of  $\text{Pd}(\text{OAc})_2$ ,  $\text{PCy}_3$  and aqueous  $\text{K}_3\text{PO}_4 \cdot \text{H}_2\text{O}$  for the synthesis of biphenyls.

Under these reaction conditions, several aryl bromides bearing electron-donating and withdrawing substituents were successfully coupled with 2-arylbenzo-1,3,2-diazaborolane compounds to afford antisymmetrical and symmetrical biphenyls in isolated yields ranging from 62-96% in 10 minutes. Substrates bearing electron-withdrawing substituents were shown to be more reactive under these reaction conditions affording biphenyls in excellent isolated yields ranging from 83% to 96%. While our yields are comparable with the yields reported in literature, our reactions take only 10 minutes (!) compared to many hours of reflux as reported in the literature.

These studies highlights a novel methodology for the preparation of both the symmetrical and antisymmetrical biphenyls from 2-arylbenzo-1,3,2-diazaborolane derivatives as potential Suzuki coupling partners. These results have been drawn up for the publication in journal of organic chemistry. For reference, a draft copy of the publication is attached below.

## 4.6References

1. Frankland, E., Duppa, B. F., *JustusLiebigs Ann. Chem.* **1860**, 115, 319.
2. Kimpe, D., N., Keppens, M., Froneg, G., *Chem. Commun.* **1996**, 635.
3. Spencer, J., Burd, A. P., Goodwin, C. A., Marette, S. A. M., Scully, M. F., Adatia, T., Deadman, J. J., *Tetrahedron* **2002**, 58, 1551.
4. Brown, G. J., Silva, A. P., Pagliari, S., *J. Am. Chem. Soc.* **2002**, 2461.
5. Georgiou, I., Ilyashenko, G., Wthiting, A., *Acc. Chem. Res.* **2009**, 42, 756.
6. Hall, D. G., *Boronic acids: Preparation and Application in Organic Synthesis and Medicine*. VCH, Weinham., 2005; p 1-99.
7. Melamed, M., Khotinsky, E., *Chem. Ber.* **1909**, 42, 3090.
8. Johnson, J. R., Seaman, W., *J. Am. Chem. Soc.* **1931**, 53, 711.
9. Cladingboel, D. E., *Org. Res. Devel.* **2000**, 4, 153.
10. Zenk, R., Partzsch, S., *Chim. Oggi.* **2003**, 70.
11. Blatch, A. J., Chetina, O. V., Howard, J. A. K., Patric, L. G. F., Smethurst, C. A., Whiting, A., *Org. Biomol. Chem.* **2006**, 4.
12. Wong, K.-T., Chien, T.-T., Liao, Y.-L., Lin, C.-C., Chou, M.-Y., Leung, M.-K., *J. Org. Chem.* **2002**, 67, 1041.
13. Garg, N. K., Sarpong, R., Stoltz, B. M., *J. Am. Chem. Soc.* **2002**, 124, 13179.
14. Lauer, M., Wulff, G., *J. Organomet. Chem.* **1983**, 256, 1.
15. Sharp, M. J., Snieckus, V., *Tetrahedron Lett.* **1985**, 49, 5997.
16. Larsen, R. D., King, A. O., Chen, C. Y., *J. Org. Chem.* **1994**, 59, 6391.
17. Ishiyama, T., Miyaura, N., *Chem. Rec.* **2004**, 3, 271.
18. Billingsley, K., Barder, T. E., Buchwald, S. L., *Angew. Chem. Int. Ed.* **2007**, 46, 5359.
19. Zhu, W., Ma, D., *Org. Lett.* **2006**, 8, 261.
20. Rosen, M. B., Huang, C., Percec, V., *Org. Lett.* **2008**, 10, 2597.
21. Rosen, M. B., Percec, V., Wilson, D. A., Wilson, C. J., *Org. Lett.* **2008**, 10, 4879.
22. Moldoveanu, C., Wilson, D. A., Wilson, C. J., Corcoran, P., Rosen, B. M., Percec, V., *Org. Lett.* **2009**, 11, 4974.
23. Knochel, P., Gavvryushin, A., *Synfacts* **2010**, 1, 84.
24. Wilson, D. A., Wilson, C. J., Moldoveanu, C., Resmerita, A.-M., *J. Am. Chem. Soc.* **2010**, 132, 1800.
25. Moldoveanu, C., Wilson, D. A., Wilson, C. J., Corcoran, P., Rosen, B. M., Percec, V., *J. Org. Chem.* **2010**, 75, 5438.
26. Leowanawat, P., Resmerita, A.-M., Moldoveanu, C., Liu, C., Zhang, N., *J. Org. Chem.* **2010**, 75, 7822.
27. Broutin, E.-P., Cerna, I., Campaniello, M., Leroux, F., Colobert, F., *Org. Lett.* **2004**, 24, 4419.
28. Murata, M., Sambommatsu, T., Watabane, S., Masuda, Y., *Synlett.* **2006**, 1867.
29. Billingsley, K. B., S. L., *J. Org. Chem.* **2008**, 73, 5589.
30. Thery, A., Gueiffier, A., *Eur. J. Org. Chem.* **2008**, 4824.
31. Zhou, W.-J., Wang, H.-K., Wang, J.-X., *J. Org. Chem.* **2009**, 74, 5599.
32. Chemler, S. R., Trauner, D., Dinishefsky, S. J., *Angew. Chem. Int. Ed.* **2001**, 40, 4544.
33. Yasuda, N., *J. Organomet. Chem.* **2002**, 253, 279.
34. Zhou, W.-J., Wang, H.-K., Wang, J.-X., *Eur. J. Org. Chem.* **2010**, 416.
35. Heck, R. F., *J. Am. Chem. Soc.* **1968**, 90, 5518.
36. Heck, R. F., *J. Am. Chem. Soc.* **1968**, 90, 5526.
37. Heck, R. F., *J. Am. Chem. Soc.* **1968**, 90, 5536.
38. Heck, R. F., *J. Am. Chem. Soc.* **1968**, 90, 5542.
39. Stille, K. J., Scott, J. W., *J. Am. Chem. Soc.* **1986**, 108, 3033.
40. Stille, K. J., Scott, J. W., Crisp, G. T., *J. Am. Chem. Soc.* **1984**, 106, 4630.
41. Miyaura, N., Suzuki, A., *Chem. Rev.* **1995**, 95, 2457.



42. Buchwald, S. L., Martin, R., *Chem. Res.* **2008**, 41, 1461.
43. Suzuki, A., Yamada, K., Miyaura, N., *Tetrahedron Lett.* **1979**, 20, 3437.
44. Brennfuhrer, A., Nuemann, H., Beller, M., *Angew. Chem. Int. Ed.* **2009**, 48, 4114.
45. Marion, N., Nolan, S. P., *Acc. Chem. Res.* **2008**, 41, 1440.
46. Kingston, J. V., Verkade, J. G., *J. Org. Chem.* **2007**, 72, 2816.
47. He, Y., Cai, C., *Cat. Comm.* **2011**, 12, 678.
48. Suzuki, A., Yanagi, T., Miyaura, N., *Synth. Commun.* **1981**, 11, 513.
49. Wright, S. W., Hageman, D. L., McClure, D. L., *J. Org. Chem.* **1981**, 59, 6095.
50. Watanabe, T., Miyaura, N., Suzuki, A., *Synlett.* **1992**, 207.
51. Zhang, H., Chan, K.S., *Tetrahedron Lett.* **1996**, 37, 1043.
52. Dreher, D. S., Lim, S.-Ee., Sandrock, L.D, Molander, G. A., *J. Am. Chem. Soc.* **2009**, 74, 3626.
53. Cheng, J., Wang, F., Xu, H.-J., Pan, Y., Zhang, Z., *Tetrahedron Lett.* **2003**, 44, 7095.
54. Bellina, F., Carpita, A., Rossi, R., *Synthesis* **2004**, 2419.
55. Pan, C., Liu, M., Zhang, Wu, H., Ding, J., Cheng, J., *Cat. Comm.* **2008**, 9, 508.
56. Korolven, D. N., Bumagin, N. A., *Tetrahedron Lett.* **2006**, 47, 4225.
57. Andrio, A. L., Nguyen, N. B., Guilera, G., Livingston, G. A., Hii, K. K., *Catal. Sci. Technol.* **2012**, 2, 316.
58. Kantam, M. L., Subhas, M. S., Roy, S., Roy, M., *Synlett.* **2006**, 633.
59. Trzeciak, A. M., Ziolkowski, J., *Coord. Chem. Rev.* **2007**, 251, 1281.
60. Martins, D., de L., Alvarez, M. H., Aguiar, C. S. L., *Tetrahedron Lett.* **2010**, 51, 6814.
61. Astruc, D., *In Nanoparticles and Catalysis; Wiley-VCH: Weinheim*, 2008; Vol. 1, p 1.
62. Lorenzo, P. M., *J. Phys. Chem. Lett.* **2012**, 3, 167.
63. Percec, V., Bae, Y.-J., Hill, H. D., *J. Org. Chem.* **1995**, 60, 1060.
64. Zim, D., Monteiro, L. A., Lando, R. V., Dupont, J., *Org. Lett.* **2001**, 3, 3049.
65. Zim, D., Monteiro, L. A., *Tetrahedron Lett.* **2002**, 43, 4009.
66. Lee, C.-C., Ke, W., Chan, T.-K., Lai, C.-L., Hu, H.-C., Lee, M. H., *Chem. Eur. J.* **2077**, 13, 582.
67. Chen, C., Yang, M.-L., *Tetrahedron Lett.* **2007**, 48, 2427.
68. Tang, Y.-Z., Hu, Q.-S., *J. Am. Chem. Soc.* **2004**, 126, 3058.
69. Inamoto, K., Kuroda, J.-I., Kwon, E. Hiroya, K., Doi, T., *J. Organomet. Chem.* **2009**, 694, 389.
70. Tu, T., Mao, H., Herbert, C., Xu, M., Dotz, K. H., *Chem. Commun.* **2010**, 46, 7796.
71. Fan, H.-X., Yang, L.-M., *Eur. J. Org. Chem.* **2010**, 2457.
72. Bellina, F., Cauteruccio, S., Rossi, R., *Curr. Org. Chem.* **2008**, 12, 774.
73. Pu, L., *Chem. Rev.* **1998**, 98, 2405.
74. Wallow, T. I., Novak, B. M., *J. Org. Chem.* **1994**, 59, 5034.
75. Molander, G. A., Beaumard, F., *Org. Lett.* **2010**, 12, 4022.
76. Molander, G. A., Canturk, B., *Angew. Chem. Int. Ed.* **2009**, 48, 9240.
77. Molander, G. A., Canturk, B., Kennedy, L. E., *J. Org. Chem.* **2009**, 74, 973.
78. Knapp, D. M., Gills, E. P., Burke, M. D., *J. Am. Chem. Soc.* **2009**, 131, 6961.
79. Suzuki, A., Yamada, K., Miyaura, N., Suginome, H., *J. Am. Chem. Soc.* **1985**, 107, 972.
80. Kochi, J. K., *Organometallic Mechanisms and Catalysis*, . Academia, New York, 1978.
81. Hegedus, L. S., *Organometallic in Organic Synthesis*, . Schosser. Wiley, New York, , 1994.
82. Soderquist, J. A., Matos, K., *J. Org. Chem.* **1998**, 63, 461.
83. Miyaura, N., Suzuki, A., Yamada, K., *Tetrahedron Lett.* **1979**, 20, 3437.
84. (a) Hadebe, S. W., Robinson, R. S., *Eur. J. Org. Chem.* **2006**, 4898. (b) Denk, M. K. K., *Compounds of Boron and Aluminium*, Chapter 3, web: [http://131.104.156.23/Lectures/331/331 Chapter 3.html](http://131.104.156.23/Lectures/331/331%20Chapter%203.html) [ Date of access is 22 August 2013]

85. Schweizer, S., Eickhoff, D., Brockhinke, R., Cherian, D., Weber, L., Brockhinke, A., *Phys. Chem. Chem. Phys.* **2011**, 13, 9301.
86. Suzuki, A., *Chem. Rev.* **1995**, 95, 2457.
87. Thilanger, P.; Narayanan, S. R.; Chandrasekhar, V., *Organometallics*. **2009**, 28, 5882-5888.
88. Zhang, L., Wang, L., Li, H., Li, P., *Synth. Commun.* **2008**, 38, 1498.
89. Bezier, D., Darcel, C., *Adv. Synth. Catal.* **2009**, 351, 1732.
90. Desmarets, C., Oma-A., R., Walcarius, A., Lambert, J., Champagne, B., Fort, Y., Schnieder, R., *etrahedron* **2008**, 64, 372.
91. Truce, W., E., Tate, D. P., Burdge, D. N., *J. Am. Chem. Soc.* **1960**, 82, 2872.
92. Quasdorf, W. K., Rieher, M., Petrova, V. K., Garg, K. N., *J. Am. Chem. Soc.* **2009**, 131, 17748.
93. Wang, L., Lu, W., *Org. Lett.* **2009**, 11, 1079.
94. Chandrasekhar, V., Thilanger, P., Narayanan, S. R., *Organometallics* **2009**, 28, 5882.
95. Qin, C., Lu, W., *Org. Lett.* **2008**, 73, 7424.
96. Snieckus, V., Blackburn, T., Finch, A.-A., *J. Am. Chem. Soc.* **2009**, 131, 17750.
97. Wei, J.-F., Jiao, J., Feng, J.-J., Lv, J., Zhang, X.-R., Shi., X.-Y., Zhan-G., *J. Org. Chem.* **2009**, 6283.
98. Marcuccio, S. M., Dannock, M. C., O'Keefe, D. F., *Tetrahedron Lett.* **1992**, 33, 6679.
99. Seganish, W. M., DeShong, P., *J. Org. Chem.* **2004**, 69, 6790.
100. Itoh, Y., Brossi, A., Hamel, E., Lun, C. M., *Helvetica Chemica Acta* **1988**, 71, 1199.
101. Schweizer, S., Becht, M.-J., Drian, L. D., *Tetrahedron* **2010**, 66, 765.
102. Malanesi, S., Fagoni, S., Albini, P., *J. Org. Chem.* **2005**, 70, 603.
103. Metallinos, C., Barrett, F. B., Chaytor, J. L., Heska, M. E. A., *Org. Lett.* **2004**, 6, 3641.
104. Saito, S., Oh-tani, S., Miyaura, N., *J. Org. Chem.* **1997**, 62, 8024.
105. Zhang, G., *Chem. Research.* **2004**, 9, 593.
106. Nakamichi, N., Kawabota, H., Hayashi, M., *J. Org. Chem.* **2003**, 68, 8272.
107. Yashuba, T., Hiroyuku, W., Michiyo, N., Tetsuya, S., Masahiro, M., Masakatsu, N., *J. Org. Chem.* **2003**, 68, 5236.
108. Dikerman, C. S., Klain, M. V., George, B., *J. Org. Chem.* **1964**, 29, 3639.

# Chapter Five

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## 5. Experimental

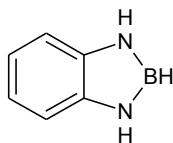
### 5.1 Chemical and Instrumental:

All reaction were carried out under nitrogen and/or argon atmosphere in an oven-dried glassware containing a magnetic stirrer bar and dry septum. Toluene was freshly distilled from Na/benzophenone prior to use. All arylboronic acids were prepared according previously published literature methods.<sup>1,2</sup> Microwave reactions were performed in a CEM Discover synthetic microwave using a 10 cm microwave tube equipped with a magnetic stirrer bar and reaction vessel cap. <sup>1</sup>H NMR (400 MHz), <sup>13</sup>C NMR (100 MHz) and <sup>11</sup>B NMR (128 MHz) were recorded on a Bruker Avance III 400 (9.4 T) spectrometer in a normal glass NMR tubes. All the NMR spectra were recorded as solution in specified deuterated solvents and are reported in parts per million (ppm) downfield from tetramethylsilane (TMS) as internal standard. <sup>11</sup>B NMR spectra were referenced to BF<sub>3</sub>:OEt<sub>2</sub> (External, neat, with capillary tube of acetone-d<sub>6</sub> for the deuterium lock). Melting points were measured on a Reichert Austria apparatus using 22×22 mm deck Glaser and are uncorrected.

High-resolution mass spectra (HRMS) were obtained on a Waters Acquits LCT premier (TOF) ultra-performance liquid chromatography-mass spectrometry. Low resolution (Electron Impact) mass spectra were acquired on a Thermo Finnigan trace GC, coupled with a Polaris Q mass spectrometer. UV studies were conducted on CARRY 100 Bio UV visible spectrometry in specified solvents. Infrared was recorded using ID, Fourier Transform Infrared instrument. Samples were placed on a diamond and compressed with infrared pressure steel. Purifications of the products were performed by centrifugal preparative thin-layer chromatography (chromatotron) and flash column chromatography on Merk silica gel cat. No. 1.07749 and Fluka silica gel 60 cat No.70-230 mesh (0.063-0.2mm), respectively.

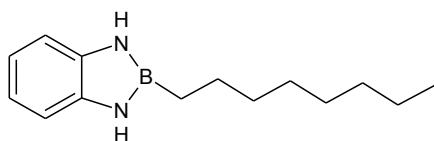
## 5.2 EXPERIMENTAL FOR CHAPTER TWO

### 5.2.1 Synthesis of 2-Benzo-1,3,2-dizaborolane (79)



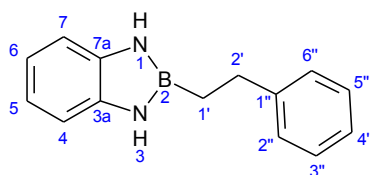
1,2-Diaminobenzene (0.54 g, 5.00 mmol) was dissolved in dichloromethane (5.0 ml) in a flame dried round-bottomed flask. After complete dissolution of the solid, borane-dimethyl sulphide complex (5.0 ml, 5.00 mmol) was introduced dropwise through the septum. The resulting mixture was stirred under reflux for 5 hrs under a dry atmosphere of nitrogen. Benzo-1,3,2-diazaborolane was obtained as a clear liquid (95%, based on  $^{11}\text{B}$  NMR analysis).  $^{11}\text{B}$  NMR (160 MHz,  $\text{BF}_3 \cdot \text{OEt}_2$ ):  $\delta$  ppm 23.9 (d,  $J = 153.2$  Hz,  $^1\text{H}$ , BH).

### 5.2.2 Synthesis of 2-octyl-benzo-1,3,2-diazaborolane (81). General method A.



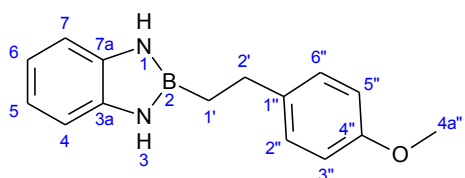
A freshly prepared benzo-1,3,2-diazaborolane solution (20.0 ml, 46.2 mmol) in DCM was injected in an oven-dried, nitrogen purged two neck round bottomed flask, followed by 1-octene (7.3 ml, 46.2 mmol) with continuous stirring. To this solution was added the DCM solution of Wilkinson catalyst (2.0 mol%, 855 mg), which was prepared in a separate flame-dried, and nitrogen flushed flask. The reaction mixture was stirred at 25 °C for 24 hr followed by the evaporation of the volatiles. The resulting orange-yellow oily product was subjected to flash column chromatography using hexane as eluting solvent. The title compound was obtained as orange-yellow wax (92%), mp 26.2-28.9 °C.  $^{11}\text{B}$  NMR (160 MHz,  $\text{BF}_3 \cdot \text{OEt}_2$ ):  $\delta$  ppm 31.6 (s). Ms (IE):  $m/z$  (%) 231[ $\text{M}^+$ ] (18), 230 (100), 229 (15), 145 (15), 132 (16), 119 (17), 118 (31).

### 5.2.3 Synthesis of phenethyl-benzo-1,3,2-diazaborolane (74)



Following general method A, the title compound (**74**) was synthesised from the reaction of benzo-1,3,2-diazaborolane (20.0 ml, 46.2 mmol) with styrene (5.3 ml, 46.2 mmol) and the reaction mixture was heated at *ca.* 60 °C for 48 hrs. Compound **74** was obtained as a cream powder in 81% after purification. Recrystallisation of the product from hexane afforded colourless needle-like crystals, melting point 53-54 °C.  $^{11}\text{B}$  NMR (160 MHz,  $\text{BF}_3 \cdot \text{OEt}_2$ ):  $\delta$ ppm 31.2 (s).  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ ):  $\delta$ ppm 1.49 (t,  $J = 7.9$  Hz, H-1', 2H), 2.80 (t,  $J = 8.1$  Hz, H-2', 2H), 6.18 (s, H-1,3, 2H), 6.77-6.81 (m, H-5,6, 2H), 6.82-6.87 (m, H-4,7, 2H), 7.09-7.25 (m, H-2'' to H-6'', 5H).  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ ):  $\delta$ ppm 31.9 (C-1',2'), 110.4 (C-4,7), 118.9 (C-5,6), 125.7 (C-3'',5''), 128.0 (C-4''), 128.4 (C-2'', 6''), 136.1 (C-3a, 7a), 144.3 (C-1''). MS (EI):  $m/z$  (%) 233 [ $\text{M}^+$ ] (16), 222 (100), 221 (27), 132 (17), 131 (44), 118 (29). HSMS found [ $\text{M}^+$ ] 221.1247, calculated for  $\text{C}_{14}\text{H}_{14}\text{N}_2\text{B}$  221.1250. IR (neat), 3385, 3364, 3027, 1621  $\text{cm}^{-1}$ .

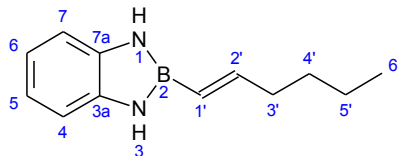
### 5.2.4 Synthesis of 2-{2-(4-methoxyphenyl)-ethyl}-benzo-1,3,2-diazaborolane (75).



Following general method A, benzo-1,3,2-diazaborolane (20.0 ml, 46.2 mmol) was reacted with 4-vinylanisole (5.61 ml, 46.2 mmol) at *ca.* 60 °C for 60 hrs. The title compound was obtained as a cream-white powder (79%), mp 128-130 °C.  $^{11}\text{B}$  NMR (160 MHz,  $\text{BF}_3 \cdot \text{OEt}_2$ ):  $\delta$  ppm 31.2 (s).  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ ):  $\delta$  ppm 4.56 (t,  $J = 8.1$  Hz, H-2', 2H), 2.85 (t,  $J = 8.0$  Hz, H-1', 2H), 3.82 (s, H-4a'', 3H), 6.29 (s, H-1,3, 2H), 6.87 (d,  $J = 8.5$  Hz, H-3'',5'', 2H), 6.90-6.94 (m, H-5,6, 2H), 6.98-7.03 (m, H-4,7, 2H), 7.19 (d,  $J = 8.8$  Hz, H-2'', 6'', 2H).  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ ):  $\delta$ ppm 30.9,

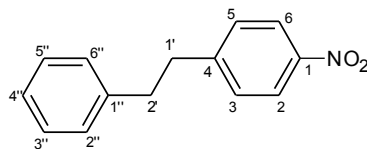
55.2, 110.5, 113.5, 140.0, 118.8, 128.8, 136.0, 136.3, 157.7. HRMS found: 251.1360  $[M^+]$ , calculated for  $C_{15}H_{17}BN_2$  is 251.1356.

### 5.2.5 Synthesis of 2-(1*E*-hexenyl)-benzo-1,3,2-diazaborolane (**86**)



1*E*-1-hexenyl-boronic acid was prepared according to known procedures.<sup>1</sup> A round bottom flask, equipped with a Dean and Stark apparatus, magnetic stirrer bar and reflux condenser, was charged with freshly prepared 1*E*-1-hexenyl-boronic acid (0.40 g, 0.31 mmol), phenylenediamine and toluene (20 ml). The resulting mixture was heated to reflux for 1h, followed by the evaporation of the solvent in *vacuo* to afford light-brown solid, which after purification through column-chromatography, afforded the title compound (**86**) as fluffy white amorphous solid (78%), mp 45-47 °C. <sup>11</sup>B NMR (160 MHz,  $BF_3 \cdot OEt_2$ ):  $\delta$  ppm 27.2 (s). <sup>1</sup>H NMR (400 MHz,  $CDCl_3$ ):  $\delta$  ppm 0.93 (t,  $J=7.3$  Hz, H-6', 3H), 1.33-1.52 (m, H-4', 5', 4H), 2.19-2.27 (m, H-3', 2H), 5.88 (dt,  $J=18.1$  Hz, H-2', 1H), 6.51 (dt,  $J=18.3$  Hz, H-1', 1H), 6.77-6.84 (m, H-5,6, 2H), 6.98-7.05 (m, H-4,7, 2H), 7.87 (s, H-1,3, 2H). <sup>13</sup>C NMR (100 MHz,  $CDCl_3$ ):  $\delta$  ppm 13.3 (C-6'), 21.9 (C-5'), 30.9 (C-4'), 35.6 (C-3'), 110.5 (C-4,7), 118.2 (C-5,6), 137.1 (C-3a, 7a), 148.0 (C-2'). IR (neat) 3381, 3360, 2961, 2928, 2874, 2856, 1634  $cm^{-1}$ . HRMS found  $[M^+]$  199.1404, calculated for  $C_{12}H_{17}BN_2$  is 199.1407.

### 5.2.6 Synthesis of 1-(4-nitrophenyl)-2phenylethane (**91**)

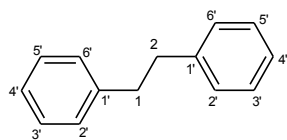


**General method B:** A microwave tube equipped with a magnetic stirrer bar was charged with 4-bromonitrobenzene (0.10 g, 0.49 mmol),  $K_3PO_4 \cdot H_2O$  (0.34 g, 1.47 mmol),  $PCy_3$  (11 mg, 0.039 mmol),  $Pd(OAc)_2$  (4.40 mg, 0.020 mmol),

<sup>1</sup> Saito, S., Oh-tani, S., Miyaura, N. *J. Org. Chem.* **1997**, 62, 8024.

2-phenethylbenzo-1,3,2-diazaborolane (0.22 g, 0.98 mmol) and toluene (0.1 ml). The reaction tube was closed with a microwave cap and irradiated with microwave energy (200W) for 15 min. After the completion of the reaction, the black resulting mixture was dissolved in acetone and filtered. The evaporation of the volatiles resulted in a black oily residue, which when purified through a column chromatography, using hexane:ethylacetate (8:2), afforded compound **2.5** as colourless crystals (57%), mp 55-56 °C. <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>): δppm 2.98 (t, *J* = 7.7 Hz, H-1', 2H), 3.05 (t, *J* = 7.7 Hz, H-2', 2H), 7.15 (d, *J* = 7.6 Hz, H-4,5, 2H), 7.23 (t, *J* = 6.9 Hz, H-4'', 1H), 7.27-7.33 (m, H-2'', 4'', 5'' and 6'', 4H), 8.14 (d, *J* = 8.6 Hz, H-2,6, 2H). <sup>13</sup>C NMR (100 MHz, CDCl<sub>3</sub>): δppm 37.2, 37.6, 123.6, 128.5, 129.4, 140.5, 146.5, 149.4. HRMS found [M<sup>+</sup>+Na<sup>+</sup>] 250.0847, calculated for C<sub>14</sub>H<sub>13</sub>NNaO<sub>2</sub> is 250.0844.

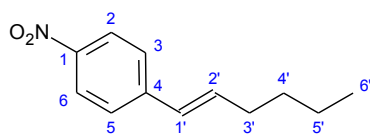
### 5.2.7 Synthesis of 1,1'-dibenzyl (93)



Following general method B, 2-phenethylbenzo-1,3,2-diazaborolane (0.11 g, 0.49 mmol) was reacted with bromobenzene (0.1 ml) to afford, after purification of the crude product, the title compound **2.6** as colourless crystals (79%) mp 51°C [lit.<sup>2</sup> 51 °C]. <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>): δppm 2.95 (s, H-1,2, 4H), 7.18-7.25 (m, H-2' to H-6', 5H), 7.26-7.34 (m, H-2' to H-6', 5H). <sup>13</sup>C NMR (100 MHz, CDCl<sub>3</sub>): δppm 37.9 (C-1,2), 125.9 (C-4'), 138.2 (C-2',6'), 138.3 (C-3',5'), 141.8 (C-1'). MS (EI): *m/z* (%) 65 (24), 91 (100), 92 (7), 104 (22), 182 (32) [M<sup>+</sup>].

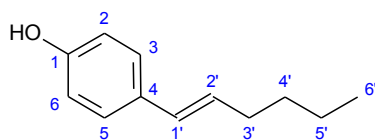
<sup>2</sup> Jourdent, A., Conzalez-Zamara, E., Zhu, J. *J. Org. Chem.* **2002**, 67, 3163.

### 5.2.8 Synthesis of 4-(1*E*-hexenyl)-nitrobenzene (**91**)



**General Method C:** A microwave tube equipped with a magnetic stirring bar was charged with 2-(1*E*-hexenyl)-benzo-1,3,2-diazaborolane (**91**) (0.20 g, 0.10 mmol),  $K_3PO_4 \cdot H_2O$  (0.35 g, 1.50 mmol),  $PCy_3$  (11.2 g, 0.040 mmol),  $Pd(OAc)_2$  (4.40 mg, 0.020 mmol), 1,4-dioxane (0.2 ml), and the corresponding aryl halide (0.5 mmol). The reaction tube was closed with a microwave cap and irradiated with 15W of microwave energy for 20 minutes at 100 °C. After the completion of the reaction, the content of the flask was dissolved in acetone, filtered and the solvent evaporated to dryness to afford a black residue which was purified through silica gel chromatography using hexane: ethyl acetate (9:1). Following general method C, 4-bromonitrobenzene (0.10 g, 0.50 mmol) was reacted with compound **91** to afford the title compound as clear-yellow oily product (81%).  $^1H$  NMR(400 MHz,  $CDCl_3$ ): $\delta$ ppm 0.95 (t,  $J = 7.5$  Hz, H-6', 3H), 1.34-1.56 (m, H-4',5', 4H), 2.25-2.31 (m, H-3', 2H), 6.44-6.47 (m, H-1',H-2', 2H), 7.46 (d,  $J = 8.9$  Hz, H-3,5, 2H), 8.16 (d,  $J = 9.0$  Hz, H-2, 6, 2H).  $^{13}C$  NMR (100 MHz,  $CDCl_3$ ): $\delta$  ppm 13.8 (C-6'), 22.2 (C-5'), 31.1 (C-4'), 32.8 (C-3'), 123.9 (C-2,6), 126.3 (C-3,5), 128.0 (C-2'), 136.6 (C-1'), 144.4 (C-4), 146.4 (C-1). IR (neat) 2957, 2928, 1595, 1512, 1337, 1108  $cm^{-1}$ . HRMS found  $[M^+ + Na^+]$  228.0999, calculated for  $C_{12}H_{15}NO_2Na$  is 228.1000.

### 5.2.9 Synthesis of 4-(1*E*-hexenyl)-phenol (**96**)

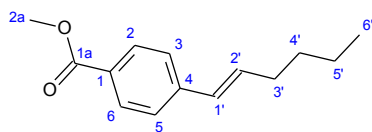


Following general method C, the title compound was successfully synthesised from 4-bromophenol (0.086 g, 0.50 mmol) and compound **96** in 67% as a colourless oil.  $^1H$  NMR(400 MHz,  $CDCl_3$ ): $\delta$ ppm 0.93 (t,  $J = 7.0$  Hz, H-6', 3H), 1.36-1.50 (m, H-4',5', 4H), 2.16-2.23 (m, H-3', 2H), 6.08 (dt,  $J = 15.8$  Hz, H-2', 1H), 6.30 (d,  $J = 15.8$  Hz,



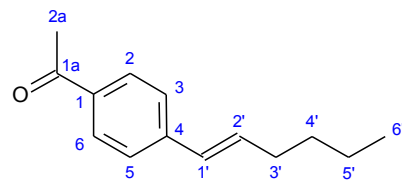
H-1', 1H), 6.77 (d,  $J = 8.6$  Hz, H-3,5, 2H), 7.23 (d,  $J = 8.5$  Hz, H-2,6, 2H).  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ ): $\delta$ ppm 13.9 (C-6'), 22.2 (C-5'), 31.2 (C-4'), 32.6 (C-3'), 67.0 (C-2'), 115.4 (C-1'), 127.1 (C-1)), 129.0 (C-2,6), 129.0 (C-3,5), 154.5 (C-4). IR (neat) 3313, 2956, 2928, 1600, 1511, 1218  $\text{cm}^{-1}$ . HRMS found  $[\text{M}^+]$  175.1125, calculated for  $\text{C}_{12}\text{H}_{15}\text{O}$  is 175.1123.

### 5.2.10 Synthesis of 4-(1*E*-hexenyl)-methyl benzoate (98)



Following general procedure C, 4-bromomethylbenzoate (0.11 g, 0.50 mmol) was reacted with compound **2.5** to afford the title compound as colourless oil (67%).  $^1\text{H}$  NMR(400 MHz,  $\text{CDCl}_3$ ): $\delta$ ppm 0.95 (t,  $J = 7.2$  Hz, H-6', 2H), 1.35-1.44 (m, H-5', 2H), 1.44-1.55 (m, H-4', 2H), 2.25 (q,  $J = 6.6$  Hz, H-3', 2H), 3.92 (s, H-2a, 3H), 6.32-6.48 (m, H-1',2', 2H), 7.40 (d,  $J = 8.1$  Hz, H-3,5, 2H), 7.97 (d,  $J = 8.0$  Hz, 2H).  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ ): $\delta$  ppm 13.8 (C-6'), 22.2 (C-5'), 31.3 (C-4'), 32.8 (C-3'), 51.9 (C-2a), 125.9 (C-4'), 129.0 (C-3,5), 129.8 (C-2,6), 134.2 (C-4), 142.5 (C-1), 167.0 (C-1a). IR (neat) 2954, 2927, 1718, 1272, 1107  $\text{cm}^{-1}$ . HRMS found  $[\text{M}^+ + \text{Na}^+]$  241.1204, calculated for  $\text{C}_{14}\text{H}_{18}\text{O}_2\text{Na}$  is 241.1204.

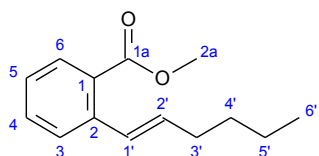
### 5.2.11 Synthesis of 4-(1*E*-hexenyl)-acetophenone (100)



Following general procedure C, 4-bromoacetophenone (0.10 g, 0.50 mmol) was reacted with compound **2.5** furnishing the title compound as colourless oil (67%).  $^1\text{H}$  NMR(400 MHz,  $\text{CDCl}_3$ ): $\delta$ ppm 0.95 (t,  $J = 7.3$  Hz, H-6', 3H), 1.33-1.43 (m, H-5', 2H), 1.43-1.56 (m, H-4', 2H), 2.21-2.29 (m, H-3', 2H), 2.58 (s, H-2a, 3H), 6.42-6.49

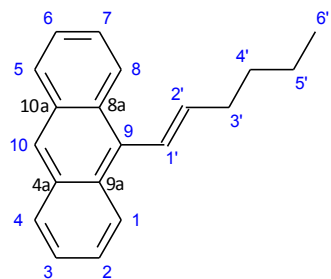
(m, H-1',2', 2H), 7.41 (d,  $J = 8.3$  Hz, H-3,5, 2H), 7.89 (d,  $J = 8.5$  Hz, H-2,6, 2H).  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ ): $\delta$ ppm 13.9 (C-6'), 22.2 (C-5'), 31.2 (C-2a), 32.8 (C-4'), 125.8 (C-3,5), 128.7 (C-2,6), 128.9 (C-2') 134.4 (C-1'), 135.4 (C-4), 142.6 (C-1), 197.4 (C-1a). MS (EI): $m/z$  (%) 103 (8), 115 (25), 131 (80), 146 (39), 159 (10), 187 (100), 202 (60) [ $\text{M}^+$ ], 202 (10). IR (neat) 2957, 2927, 1678, 1601, 1265  $\text{cm}^{-1}$ . HRMS found [ $\text{M}^+ + \text{Na}^+$ ] 225.1255, calculated for  $\text{C}_{14}\text{H}_{18}\text{ONa}$  is 225.1255.

### 5.2.12 Synthesis of 2-(1*E*-hexenyl)-methylbenzoate (102)



Following general procedure C, 2-iodomethylbenzoate (0.13 g, 0.50 mmol) was reacted with compound **2.4** to afford the title compound as colourless oil in 74% yield.  $^1\text{H}$  NMR(400 MHz,  $\text{CDCl}_3$ ): $\delta$ ppm 0.95 (t,  $J = 7.2$  Hz, H-6', 3H), 1.35-1.55 (m, H-4',5', 4H), 2.24-2.31 (m, H-3', 2H), 3.91 (s, H-2a, 3H), 6.15 (dt,  $J = 15.6$  Hz, H-2', 1H), 7.15 (m, H-1', 1H), 7.26 (dd,  $J = 7.6, 1.5$  Hz, H-3, 1H), 7.41-7.47 (m, H-4, 1H), 7.55 (dd,  $J = 7.2, 0.84$  Hz, H-5, 1H), 7.87 (dd,  $J = 7.9, 1.4$  Hz, H-6).  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ ): $\delta$  ppm 13.9, 22.2, 31.4, 32.8, 51.9, 126.4, 127.1, 128.1, 128.4, 130.2, 131.8, 134.0, 139.7, 168.0. MS (EI)  $m/z$  (%) 91 (14), 115 (24), 144 (100), 161 (69), 162 (12), 186 (7), 218 (38) [ $\text{M}^+$ ], 219 (22). IR (neat) 2954, 2927, 1720, 1247, 1076  $\text{cm}^{-1}$ . HRMS [ $\text{M}^+ + \text{Na}^+$ ] found 241.1205, calculated for  $\text{C}_{14}\text{H}_{18}\text{O}_2\text{Na}$  is 241.1204

### 5.2.13 Synthesis of 9-(1*E*-hexenyl)-anthracene (104)

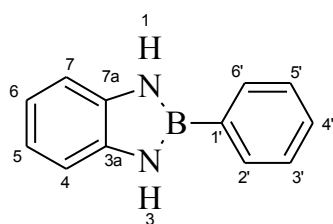


Following general procedure C, 9-bromoanthracene (0.13 g, 0.50 mmol) was reacted with compound **104** to afford the titled compound as light yellow amorphous solid,

which when recrystallised from hexane, afforded the desired product as light yellow needle-like crystals (79%), mp 53-54 °C.  $^1\text{H}$  NMR(400 MHz,  $\text{CDCl}_3$ ): $\delta$ ppm 1.06 (t, H-6', 3H), 1.52-1.62 (m, H-5', 2H), 1.64-1.75 (m, H-4', 2H), 2.50-2.58 (m, H-3', 2H), 6.08 (dt,  $J = 16.1, 6.7$  Hz, H-2, 1H), 7.14 (dt,  $J = 16.0$  Hz, H-1', 1H), 7.46-7.51 (m, H-2, 3, 6, 7, 4H), 7.99-8.05 (m, H-1,5, 2H), 8.32-8.39 (m, H-4,8,9, 3H).  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ ): $\delta$  ppm 14.1, 22.5, 31.6, 33.4, 125.0, 125.3, 125.7, 126.2, 128.1, 128.5, 129.6, 131.5, 133.7, 139.6. MS (EI):  $m/z$  (%) 189 (6), 201 (10), 202 (66), 217 (100), 218 (71), 231 (63), 260 (79) [ $\text{M}^+$ ], 261 (20). HRMS found 260.1565, calculated for  $\text{C}_{20}\text{H}_{20}$  is 260.1570.

## 5.3 EXPERIMENTAL FOR CHAPTER THREE

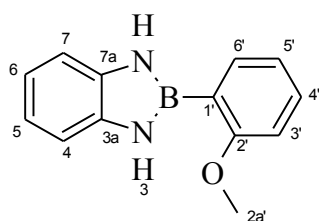
### 5.3.1 Synthesis of 2-phenylbenzo-1,3,2-diazaborole (173). General procedure D.



Arylboronic acid (1.0 equiv.) and *o*-phenylenediamine (1.0 equiv.) were dissolved in toluene (80ml) in a two neck flask equipped with a Dean and Stark Apparatus, magnetic stirrer bar and reflux condenser. This mixture was heated under reflux overnight and the solvent was removed *in vacuo*, to afford the corresponding 2-arylbenzo-1,3,2-diazaborole as a solid residue. The desired products were purified through flash column and radial chromatography using Hexane: Ethyl acetate (8:2) as an eluting solvent. The title compound was prepared according to General procedure D, using phenylboronic acid (1.00 g, 8.20 mmol) and *o*-phenylenediamine (0.89 g, 8.20 mmol) to afford 2-phenyl-1,3,2-diazaborolane **173** as a cream white crystalline product (93%). Recrystallisation of the solid residue from toluene afforded 2-phenylbenzo-1,3,2-diazaborolane **173** as a colourless round lumps mp 213-216 °C

(lit)<sup>3</sup> 212-214 °C. <sup>1</sup>H NMR (400MHz, Acetone-d<sub>6</sub>) δ<sub>H</sub>, ppm: 6.80 (s, H-1,3, 2H), 6.95-7.02 (m, H-5,6, 2H), 7.11-7.20 (m, H-4,7, 2H) 7.40-7.51 (m, H-3',4',5', 3H), 7.71-7.85 (m, H-2'6',2H). <sup>13</sup>C NMR (100 MHz, Acetone-d<sub>6</sub>) δ<sub>C</sub>, ppm: 110.9 (C-4,7), 118.6 (C-5,6), 127.9 (C-3',5'), 129.3 (C-4'), 133.3 (C-2',6'), 137.3 (C-3a,7a). <sup>11</sup>B NMR (128MHz, Acetone-d<sub>6</sub>) δ<sub>B</sub>, ppm : 28.9 { br s, CB(NH)<sub>2</sub>}. ν<sub>max</sub> (neat) 3441, 3418, 1422 cm<sup>-1</sup>. HRMS found [M<sup>+</sup>-H] = 193.0938, calculated for C<sub>12</sub>H<sub>11</sub>BN<sub>2</sub> is 194.0401.

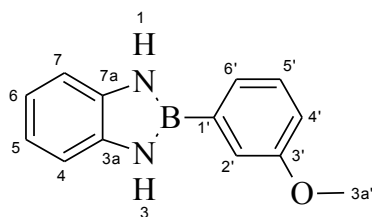
### 5.3.2 Synthesis of 2-(2-methoxyphenyl)-benzo-1,3,2-diazaborole (179)



Following general procedure D, 2-methoxyphenyl boronic acid (1.00 g, 5.18 mmol) was reacted with *o*-phenylenediamine (0.56 g, 5.18 mmol) to afford the title compound as cream white crystals (84%), mp:118-120 °C. <sup>1</sup>H NMR (400MHz, Acetone-d<sub>6</sub>) δ<sub>H</sub>, ppm: 3.98 (s, H-2a, 3H), 6.88-7.01 (m, H-4,7, 2H), 7.06-7.12 (m, H-3',5', 2H), 7.15-7.22 (m, H-5,6, 2H), 7.44-7.50 (m, H-4', 1H), 7.70 (dd, *J* = 7.3, 1.4 Hz, H-6', 1H). <sup>13</sup>C NMR (100 MHz, Acetone-d<sub>6</sub>) δ<sub>C</sub>, ppm: 55.3 (C-2a), 110.3 (C-3'), 110.9 (C-5,6), 119.0 (C-1'), 120.6 (C-4,7), 131.2 (C-5'), 134.8 (C-6'), 136.2 (C-3a, 7a), 163.6 (C-2'). IR (neat) 3467, 3423, 1434, 1418 cm<sup>-1</sup>. HRMS: found [M<sup>+</sup>-H] 223.1043, calculated for C<sub>13</sub>H<sub>13</sub>BN<sub>2</sub>O [M<sup>+</sup>] is 224.0661.

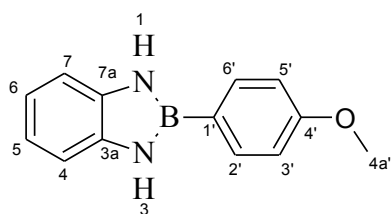
<sup>3</sup> Soloway, A. H. *J. Am. Chem. Soc.* **1959**, 82, 2442.

### 5.3.3 Synthesis of 2-(3-methoxyphenyl)benzo-1,3,2-diazaborole



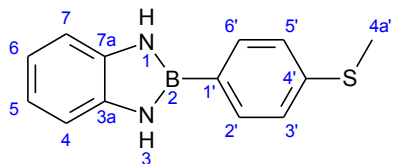
Following the general procedure D, 3-methoxyphenyl boronic acid (1.00 g, 5.18 mmol) was reacted with *o*-phenylenediamine (0.56 g, 5.18 mmol) to afford the title compound (89%) as an orange-red powder.  $^1\text{H}$  NMR (400MHz, Acetone- $\text{d}_6$ )  $\delta_{\text{H}}$ , ppm: 3.85 (s, H-3a, 3H), 6.86-6.90 (m, H-4,7, 2H), 6.98 (dd,  $J = 8.1, 2.5$  Hz, H-4', 1H), 7.05-7.23 (m, H-5,6, 2H), 7.34 (t,  $J = 7.8$  Hz, H-5', 1H), 7.48-7.54 (m, H-2',6', 2H), 8.44 (s, H-1,3, 2H).  $^{13}\text{C}$  NMR (100 MHz, Acetone- $\text{d}_6$ )  $\delta_{\text{C}}$ , ppm: 54.5 (C-OCH<sub>3</sub>), 110.9 (C-4, 7), 115.0 (C-2'), 118.3 (C-5'), 118.6 (C-5, 6), 125.5 (C-4'), 129.0 (C-6'), 137.2 (3a, 7a), 159.5 (C-3'). HRMS: found  $[\text{M}^+ - \text{H}]$  223.1043, calculated for  $\text{C}_{13}\text{H}_{13}\text{BN}_2\text{O}$   $[\text{M}^+]$ : 224.0661. IR (neat) 3414, 1425, 1410  $\text{cm}^{-1}$ .

### 5.3.4 Synthesis of 2-(4-methoxyphenyl)benzo-1,3,2-diazaborole (180)



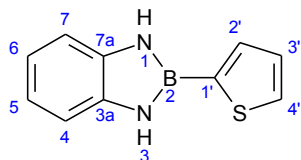
Following general procedure D, 4-methoxyphenyl boronic acid (1.00 g, 5.18 mmol) was reacted with *o*-phenylenediamine (0.56 g, 5.18 mmol) to afford the title compound as a yellowish-plate like product (78%).  $^1\text{H}$  NMR (400MHz, Acetone- $\text{d}_6$ )  $\delta_{\text{H}}$ , ppm: 3.84 (s, H-4a, 2H), 6.80-6.87 (m, H-4,7, 2H), 6.98 (d,  $J = 8.5$  Hz, H-3',5', 2H), 7.08-7.12 (m, H-5,6, 2H), 7.86 (d,  $J = 8.7$  Hz, H-2',6', 2H), 8.29 (s, H-1,3, 2H).  $^{13}\text{C}$  NMR (100 MHz, Acetone- $\text{d}_6$ )  $\delta_{\text{C}}$ , ppm: 54.4 (C-4a), 110.7 (C-3', 5'), 113.5 (C-5,6), 118.4 (C-4,7), 134.8 (C-2',6'), 137.4 (C-3a,7a), 161.0 (C-4'). HRMS: found  $[\text{M}^+ - \text{H}] = 223.1043$ , calculated for  $\text{C}_{13}\text{H}_{13}\text{BN}_2\text{O}$   $[\text{M}^+]$  is 224.0661. IR (neat) 3450, 3432, 1407  $\text{cm}^{-1}$ .

### 5.3.5 Synthesis of 2-(4-methylthiophenyl)-benzo-1,3,2-diazaborole (181).



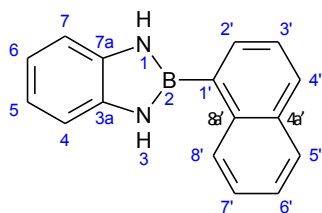
Following general procedure D, 4-methylthiophenylboronic acid (1.00 g, 5.95 mmol) was reacted with *o*-phenylenediamine (0.644 g, 5.95 mmol) to afford the title compound as a light brown solid (86%).  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{H}}$ , ppm: 2.53 (s, H-4a, 3H), 6.83-6.88 (m, H-4,7, 2H), 7.07-7.13 (m, H-5,6, 2H), 7.32 (d,  $J = 8.3$  Hz, H-3,5, 2H), 7.86 (d,  $J = 8.41$  Hz, H-2,6, 2H), 8.41 (s, H-1,3, 2H).  $^{13}\text{C}\{^1\text{H}\}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{C}}$ , ppm: 14.1 (C-4a), 110.8 (C-5,6), 118.6 (C-4,7), 125.4 (C-3',5'), 133.7 (C-2',6'), 137.3 (C-3a,7a), 140.3 (C-4a'). HRMS: found  $[\text{M}^+]$  239.0816, calculated for  $\text{C}_{13}\text{H}_{13}\text{BN}_2\text{S}$  is 239.0814. IR (neat): 3447, 3432, 1583, 1393, 1352, 816, 734  $\text{cm}^{-1}$ .

### 5.3.6 Synthesis of 2-(2-thienyl)-benzo-1,3,2-diazaborole (182)



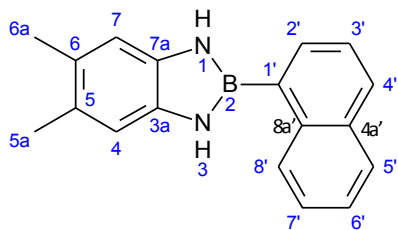
Following general procedure D, 2-thiopheneboronic acid (0.40 g, 3.13 mmol), was reacted with *o*-phenylenediamine (1.35 g, 1.25 mmol) to afford the title compound as colourless crystals (91%).  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{H}}$ , ppm: 6.73 (s, H-1,3, 2H), 6.97-7.03 (m, H-4,7, 2H), 7.10-7.16 (m, H-5,6, 2H), 7.25-7.29 (m, H-3', 1H), 7.54-7.56 (m, H-4', 1H), 7.62-7.64 (m, H-2', 1H).  $^{13}\text{C}\{^1\text{H}\}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{C}}$ , ppm: 111.9 (C-5,6), 119.5 (C-4,7), 128.5 (C-3'), 130.14 (C-2'), 133.6 (C-4'), 136.0 (C-3a,7a).

### 5.3.7 Synthesis of 2-(1-naphthyl)-benzo-1,3,2-diazaborole (183)



Following general procedure D, 1-naphthylboronic acid (0.50 g, 2.19 mmol) was reacted with *o*-phenylenediamine (0.31 g, 2.19 mmol) to afford the title compound as cream white powder (81%).  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{H}}$ , ppm: 6.72 (s, H-1,3, 2H), 6.97-7.03 (m, H-4,7, 2H), 7.10-7.16 (m, H-5,6, 2H), 7.50-7.56 (m, H-3'6'7', 3H), 7.79 (dd,  $J = 6.76, 1.01$  Hz, H-8', 1H), 7.88-7.96 (m, H-4'5', 2H), 8.25-8.31 (m, H-2', 1H).  $^{13}\text{C}\{^1\text{H}\}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{C}}$ , ppm: 19.8, 112.3, 125.2, 125.6, 126.1, 127.3, 128.2, 128.6, 129.2, 132.6, 133.3, 134.3, 136.1.  $^{11}\text{B}$  NMR (128 MHz,  $\text{DCCl}_3$ )  $\delta$ : 29.10 (s). HRMS found 243.1099, calculated for  $\text{C}_{16}\text{H}_{12}\text{BN}_2$  is 243.1094. IR (neat): 3454, 3451, 2925, 2854, 1461, 1431, 1420, 1379, 1341, 1330, 1285, 1263, 1233, 1166, 995, 857, 801, 778  $\text{cm}^{-1}$ .

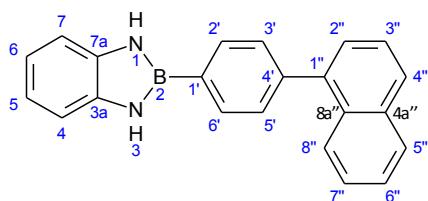
### 5.3.8 Synthesis of 2-(1-naphthyl)-4,5-dimethyl-benzo-1,3,2-diazaborole (189)



4,5-Dimethyl-*o*-phenylenediamine (0.10 g, 0.73 mmol), 1-naphthyl boronic acid (0.19 g, 1.10 mmol) and toluene (8 ml) were placed into a 100 ml round bottom flask and heated to reflux until all the solvent has evaporated. The resulting brown solid was purified by column chromatography using hexane: ethyl acetate (9:1) as an eluting solvent to afford the title compound as cream white powder (79%).  $^1\text{H}$  NMR (400

MHz, CDCl<sub>3</sub>)  $\delta_{\text{H}}$ , ppm: 2.35 (s, H-5a,6a, 6H), 6.72 (s, H-1,3, 2H), 6.99 (s, H-4,7, 2H), 7.50-7.56 (m, H-3'6'7', 3H), 7.79 (dd,  $J = 6.7, 1.0$  Hz, H-8',1H), 7.88-7.96 (m,4'5', 2H), 8.25-8.31 (m, H-2', 1H). <sup>13</sup>C{<sup>1</sup>H} NMR (100 MHz, CDCl<sub>3</sub>)  $\delta_{\text{C}}$ , ppm: 19.8, 112.3, 125.2, 125.6, 126.1, 127.3, 128.2, 128.6, 129.2, 132.6, 133.3, 134.3, 136.1. <sup>11</sup>B NMR (128 MHz, DCCl<sub>3</sub>,)  $\delta$ : 29.10 (s). HRMS found 271.1411, calculated for C<sub>18</sub>H<sub>17</sub>BN<sub>2</sub> is 271.1407. IR (neat): 3454, 3451, 2925, 2854, 1461, 1431, 1420, 1379, 1341, 1330, 1285, 1263, 1233, 1166, 995, 857, 801, 778 cm<sup>-1</sup>.

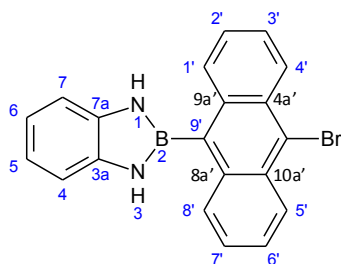
### 5.3.9 Synthesis of 2-(1-naphthyl)-phenylbenzo-1,3,2-diazaborole (190)



A mixture of 4-(1-naphthyl)-phenylboronic acid (0.13 g, 0.51 mmol), *o*-phenylenediamine (0.055 g, 0.51 mmol), toluene (5 ml) was heated to reflux in an open air until all the solvent has evaporated. The resulting light brown solid was purified by silica gel column chromatography with hexane: ethyl acetate (8:2) as eluent affording the title compounds as a white powder (64%). <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>)  $\delta_{\text{H}}$ , ppm: 6.88 (s, H-1,3, 2H), 6.97-7.06 (m, H-4,7, 2H), 7.12-7.21 (m, H-5,6, 2H), 7.42-7.58 (m, H-2'',3'',6'',7'', 4H), 7.60 (d,  $J = 8.0$  Hz, H-3',5', 2H), 7.73-7.79 (m, H-8'', 1H), 7.88 (d,  $J = 8.0$  Hz, H-2',6', 2H), 7.91-8.02 (m, H-4'',5'', 2H). <sup>13</sup>C{<sup>1</sup>H} NMR (100 MHz, CDCl<sub>3</sub>)  $\delta_{\text{C}}$ , ppm: 111.0, 111.3, 125.3, 125.5, 125.7, 126.0, 126.8, 127.0, 127.7, 127.9, 128.2, 128.4, 129.8, 130.0, 131.5, 132.8, 133.0, 133.8, 136.3, 140.0, 142.2. HRMS: found [ $\text{M}^+$ ] 320.1496, calculated for C<sub>22</sub>H<sub>17</sub>BN<sub>2</sub> is 320.1485. IR (neat): 3439, 3048, 1610, 1438, 1431, 1393, 1352, 1270, 1248, 838, 797, 771, 737, 696 cm<sup>-1</sup>.

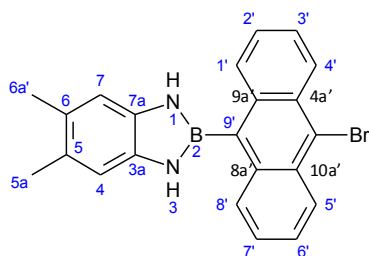


### 5.3.10 Synthesis of 2-(10-bromo-9-anthryl)benzo-1,3,2-diazaborole (172)



A 50 ml round-bottomed flask containing a magnetic stirrer bar was charged with 10-bromoanthracene-9-boronic acid (0.20 g, 0.67 mmol), *o*-phenylenediamine (0.14 g, 1.33 mmol) and toluene (10 ml). The reaction mixture was heated under reflux until all the solvent has evaporated. The residue was dissolved in acetone and purified by column chromatography using hexane: ethyl acetate (9:1) to provide the titled compound as a yellow powder (92%).  $^1\text{H}$  NMR (400 MHz, acetone- $d_6$ )  $\delta_{\text{H}}$ , ppm: 6.98–7.05 (m, H-4,7, 2H), 7.27–7.32 (m, H-5,6, 2H), 7.49–7.56 (m, H-3',6', 2H), 7.66–7.72 (m, H-2',7', 2H), 8.17 (d,  $J$  = 8.6 Hz, H-4',5', 2H), 8.58 (d,  $J$  = 8.7 Hz, H-1',8', 2H).  $^{13}\text{C}$  { $^1\text{H}$ } NMR (100 MHz, acetone- $d_6$ )  $\delta_{\text{C}}$ , ppm: 111.2 (C-5,6), 119.0 (C-4,7), 123.0 (C-10'), 125.3 (C-3',6'), 127.2 (C-2',7'), 127.4 (C-1',8'), 130.0 (3a,7a), 130.2 (C-4',5'), 136.0 (C-4a,10a), 137.1 (C-8a',9a'). HRMS: found  $[\text{M}^+]$  293.1259, calculated for  $\text{C}_{20}\text{H}_{16}\text{BrN}_2$  is 293.1250. IR (neat): 3459, 3454, 3034, 2951, 2921, 2867, 2850, 2040, 1430, 1304, 1274, 1253, 1162, 743, 726, 696  $\text{cm}^{-1}$ .

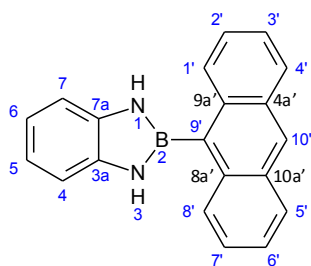
### 5.3.11 Synthesis of 2-(10-bromo-9-anthryl)-4,5-dimethylbenzo-1,3,2-diazaborole (189)



A 100 ml round bottomed-flask equipped with a stirred bar, Dean and Stark apparatus and reflux condenser was charged with 10-bromoanthracene-9-boronic acid (0.40 g,

1.34 mmol), 4,5-dimethyl-*o*-phenylenediamine (0.36 g, 2.68 mmol) and toluene (50 ml). The reaction mixture was heated to reflux with continuous withdrawal of the solvent from the side arm of Dean and Stark apparatus until all the solvent has evaporated. The remaining brown solid was cooled to room temperature and dissolved in acetone. The crude product was purified through silica gel with hexane: ethyl acetate (9:1) as eluent affording the titled compound as yellow crystalline product (86%).  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{H}}$ , ppm: 2.38 (s, H-5a,6a, 6H), 6.77 (s, H-1,3, 2H), 7.04 (s, H-4,7, 2H), 7.37-7.44 (m, H-3',6', 2H), 7.56-7.63 (m, H-2',7', 2H), 8.08 (d,  $J = 8.6$  Hz, H-4',5', 2H), 8.60 (d,  $J = 8.8$  Hz, H-1',8', 2H).  $^{13}\text{C}$   $\{^1\text{H}\}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{C}}$ , ppm: 19.8 (C-5a,6a), 112.4 (C-5,6), 124.4 (C-4,7), 125.3 (C-10'), 126.8 (C-3',5'), 127.6 (C-2',7'), 128.0 (C-1',8'), 128.0 (C-3a,7a), 130.1 (C-4',5'), 134.2 (4a', 10a'), 136.0 (C-8a',9a').

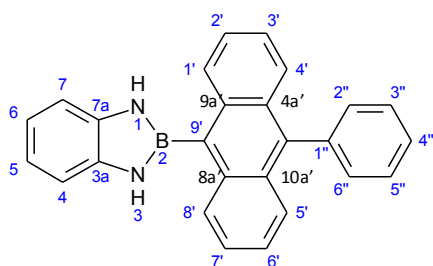
### 5.3.12 Synthesis of 2-(9-anthryl)-benzo-1,3,2-diazaborole (184)



A single-neck 100 ml round bottomed flask was charged with magnesium turnings (0.36 g, 1.5 equiv.) and dry THF (5 ml). 9-Bromoanthracene solution (0.60 g, 2.52 mmol) in dry THF (5 ml) was added dropwise to the flask containing magnesium turnings until the solvent has started refluxing. After the reaction has reached room temperature, THF (40 ml) was added and the reaction mixture was cooled to  $-78^\circ\text{C}$ . Trimethylborate solution (1.12 ml, 10.08 mmol) was added *via* a disposable syringe while the temperature is maintained at  $-78^\circ\text{C}$ . After the Addition of trimethylborate solution, the reaction mixture was allowed to reach room temperature and stirred overnight. Excess magnesium was filtered off and the solvent evaporated to dryness. To the resulting light yellow solid, was added toluene (10 ml) and *o*-phenylenediamine (0.27 g, 2.52 mmol). The mixture was heated to reflux in an open air until all the solvent has evaporated. The crude product was purified by silica gel chromatography with hexane: ethyl acetate (9:1) as eluting solvent affording the title compound as colourless plates like solid (52%).  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{H}}$ , ppm: 6.95 (br. s, 2H), 7.06-7.13 (m, H-4,7, 2H), 7.22-7.30 (m, H-5,6, 2H), 7.37-7.44 (m,

H-3',6',2H), 7.44-7.51 (m, H-2',7',2H), 8.05 (d,  $J = 8.4$  Hz, 4',5', 2H), 8.12 (d,  $J = 8.8$  Hz, H-1',8', 2H), 8.52 (s, H-10', 1H).  $^{13}\text{C}\{^1\text{H}\}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{C}}$ , ppm: 111.3 (C-5,6), 119.5 (C-4,7), 125.0 (C-10'), 125.2 (C-3'5'), 127.1 (C-2'7'), 127.9 (C-1',8'), 128.7 (C-3a,7a), 129.3 (C-4',5'), 131.1 (C-4a',10a'), 133.4 (C-8a',9a'). HRMS: found  $[\text{M}^+]$  293.1259, calculated for  $\text{C}_{20}\text{H}_{14}\text{BN}_2$  293.1250. IR (neat): 3434, 3048, 2959, 1438, 1401, 1308, 1259, 1162, 1092, 1010, 790, 734  $\text{cm}^{-1}$ .

### 5.3.13 Synthesis of 2- {9-anthryl-10-(1-phenyl)}-benzo-1,3,2-diazaborole (185).

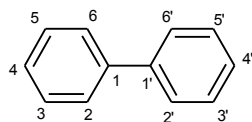


A 50 ml round bottomed-flask equipped with a magnetic stirrer bar was charged with 10-phenyl-9-anthracenyl boronic acid (0.18 g, 0.60 mmol), *o*-phenylenediamine (0.30g, 1.19 mmol) and toluene (25 ml). The mixture was heated to reflux until all the solvent has evaporated, cooled to room temperature and dissolved in acetone. The crude product was purified through silica-gel using hexane: ethyl acetate (8:2) as eluent affording the title compound as yellow powder (43%).  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{H}}$ , ppm: 6.97 (s, 2H), 7.09-7.17 (m, 2H), 7.25-7.32 (m, 2H), 7.34-7.45 (m, 4H), 7.45-7.54 (m, 2H), 7.55-7.69 (m, 3H), 7.74 (d,  $J = 8.26$  Hz, 2H), 8.17 (d,  $J = 8.38$  Hz, 2H).  $^{13}\text{C}\{^1\text{H}\}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{C}}$ , ppm: 111.3, 119.6, 124.9, 125.0, 127.3, 127.5, 128.4, 129.5, 129.7, 131.2, 135.1, 136.2, 138.4, 139.0. HRMS found 369.1558, calculated for  $\text{C}_{26}\text{H}_{19}\text{BN}_2$  is 369.4563.

## 5.4 EXPERIMENTAL FOR CHAPTER FOUR

**General procedure E:** A microwave tube equipped with a magnetic stirrer bar was charged with the corresponding 2-arylbenzo-1,3,2-diazaborole (1.0 equiv.), Pd(OAc)<sub>2</sub> (4.0 mol %) and PCy<sub>3</sub> (8.0 mol %). The tube was fitted with a rubber septum and continuously purged with argon gas for 20 minutes. In a separate 10 ml round bottomed flask, K<sub>3</sub>PO<sub>4</sub>·H<sub>2</sub>O (3.0 equiv.) was dissolved in water (0.2 ml) and aryl bromide (0.50 ml) was added. The flask was fitted with a rubber septum and argon was bubbled through the solution for 20 minutes. The contents of the round bottom flask was transferred *via* a cannula into a microwave tube which was capped and immediately irradiated in a closed vessel with 80W of microwave energy at 100 psi and 100 °C for 10 minutes. The reaction resulted in a black solid residue and an upper liquid layer. The reaction mixture was diluted with dichloromethane (5.0 ml), filtered and concentrated *in vacuo*. The resulting black residue was purified through a flash and radial chromatography using hexane: ethyl acetate (9:1) as eluting solvent.

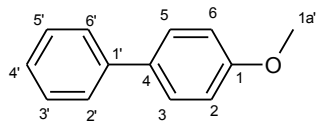
### 5.4.1 Synthesis of biphenyl (253)



Following general procedure E, 2-phenylbenzo-1,3,2-diazaborole **173** (0.15 g, 0.77 mmol) was coupled with bromobenzene **252** (0.50 ml) to afford **253** as cream white crystalline product (0.098 g, 88%): mp 69-70 °C (lit.<sup>4</sup>: 69-70 °C). <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>) δ<sub>H</sub>, ppm: 7.34-7.40 (m, 2H), 7.42-7.50 (m, 4H), 7.59-7.64 (m, 4H). <sup>13</sup>C{<sup>1</sup>H} NMR (100 MHz, CDCl<sub>3</sub>) δ<sub>C</sub>, ppm: 127.1 (C-2', 2, 6', 6), 127.2 (C-4', 4), 128.7 (C-3', 3, 5', 5). MS (EIMS): *m/z* (%) 154 [M<sup>+</sup>] (100%), 153 (41%), 152 (34%), 155 (14%), 151 (11%). IR (neat): 3034, 1478, 1428, 1345, 1170, 1042, 1006 cm<sup>-1</sup>.

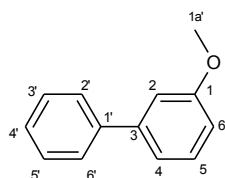
<sup>4</sup> Zhang, L.; Wang, L.; Li, H.; Li, P. *Synth. Commun.* **2008**, 38, 1498

## 5.4.2 Synthesis of 4-phenylanisole (254)



Following general procedure E, 2-phenylbenzo-1,3,2-diazaborole **173** (0.15 g, 0.77 mmol) was reacted with 4-bromoanisole **156** (0.50 ml) to afford **254** as a white powder (62%): mp 90-91°C (lit.<sup>5</sup>: 90-91°C). <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>) δ<sub>H</sub>, ppm: 3.89 (s, 3H), 7.00 (d, *J* = 8.9 Hz, 2H), 7.31-7.39 (m, 1H), 7.43 (t, *J* = 7.8 Hz, 2H), 7.55-7.64 (m, 4H). <sup>13</sup>C {<sup>1</sup>H} NMR (100 MHz, CDCl<sub>3</sub>) δ<sub>C</sub>, ppm: 55.3 (C-1a'), 114.2 (C-2, 6), 126.6 (C-4'), 126.7 (C-2; 6'), 128.1 (C-3', 5'), 128.7 (C-3, 5), 133.8 (C-4), 140.8 (C-1'), 159.2 (C-1). MS (EIMS) *m/z* (%): 184 [M<sup>+</sup>] (100%), 169 (77%), 141 (60%), 115 (32%), 185 [M<sup>+</sup> + 1] (15%). IR (neat): 3034, 3003, 2963, 2837, 1891, 1604, 1582, 1521, 1484, 1464, 1438, 1450, 1407, 1344, 1286, 1248, 1219, 1119, 1034 cm<sup>-1</sup>.

## 5.4.3 Synthesis of 3-phenylanisole (180)



Following general procedure E, 2-(3-methoxyphenyl)-benzo-1,3,2-diazaborole (0.20 g, 0.89 mmol) was reacted with bromobenzene **252** (0.50 ml) to afford **180** as a colorless oil<sup>6,7</sup> (72%): <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>) δ<sub>H</sub>, ppm: 3.90 (s, 3H), 6.93 (dd, *J* = 8.3, 2.6 Hz, 1H), 7.15-7.18 (m, 1H), 7.20-7.24 (m, 1H), 7.36-7.42 (m, 2H), 7.44-7.50 (m, 2H), 7.60-7.65 (m, 2H). <sup>13</sup>C {<sup>1</sup>H} NMR (100 MHz, CDCl<sub>3</sub>) δ<sub>C</sub>, ppm: 55.3 (C-1a'), 112.7 (C-6), 112.9 (C-2), 119.7 (C-4), 127.2 (C-3', 5'), 127.4 (C-4'), 128.7 (C-2', 6'), 129.7 (C-5), 141.1 (C-1'), 142.8 (C-3), 159.9 (C-1). MS (EIMS) *m/z* (%): 184 [M<sup>+</sup>] (100%), 154 (38%), 115 (24%), 155 (24%), 115 (23%), 153 (21%), 141

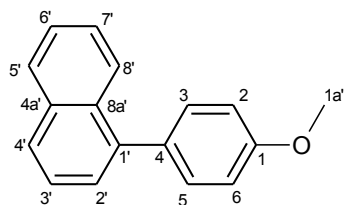
<sup>5</sup> Desmarests, C.; Omar-Amrani, R.; Walcarius, A.; Lambert, J.; Champagne, B.; Fort, Y.; Schneider, R. *Tetrahedron* **2008**, *64*, 372.

<sup>6</sup> Bolliger, J. L.; Fresh, C. M. *Chem-Eur. J.* **2010**, *16*, 4075.

<sup>7</sup> Wei, C.; Pinhua, L.; Lui, W. *Tetrahedron* **2011**, *67*, 318.

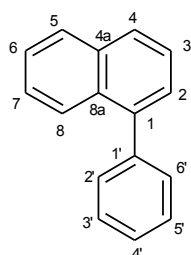
(16%), 185 [ $M^+ + 1$ ] (15%). IR (neat): 2934, 1558, 1464, 1418, 1356, 1585, 1238, 1182, 1136, 1013  $\text{cm}^{-1}$ .

#### 5.4.4 Synthesis of 1-(4-methoxyphenyl)-naphthalene (256)



Following general procedure E, 2-(1-naphthyl)-benzo-1,3,2-diazaborole (**183**) (0.20 g, 0.82 mmol) was reacted with 4-bromoanisole **156** (0.50 ml) to afford **256** as colourless crystals (68%): mp 116-117 °C (lit.<sup>8</sup>: 116-117 °C).  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{H}}$ , ppm: 3.92 (s, 3H), 7.05 (d,  $J = 8.7$  Hz, 2H), 7.40-7.47 (m, 4H), 7.47-7.55 (m, 2H), 7.85 (d,  $J = 8.3$  Hz, 1H), 7.93 (t,  $J = 9.1$  Hz, 2H).  $^{13}\text{C}\{^1\text{H}\}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{C}}$ , ppm: 55.36 (C-1a'), 113.7 (C-2, 6), 125.4 (C-2'), 125.7 (C-6'), 125.9 (C-7') 126.0 (C-5'), 12.9 (C-4'), 127.3 (C-8'), 128.2 (C-3') 131.1 (C-3, 5), 131.8 (C-4a'), 133.1 (C-8a'), 133.8 (C-4), 139.9 (C-1'), 158.9 (C-1). MS (EIMS)  $m/z$  (%): IR (neat): 2922, 2852, 1895, 1737, 1607, 1505, 1462, 1438, 1393, 1282, 1240, 1174, 1106, 1030  $\text{cm}^{-1}$ .

#### 5.4.5 Synthesis of 1-(phenyl)-naphthalene (257)



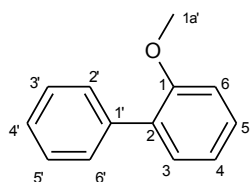
Following general procedure E, 2-(1-naphthyl)benzo-1,3,2-diazaborole (0.10 g, 0.50 mmol) was reacted with bromobenzene **252** (0.5 ml) to afford **257** as a colourless oil<sup>9</sup>

<sup>8</sup> Wang, L.; Lu, W. *Org. Lett.* **2009**, *11*, 1079.

<sup>9</sup> Nandurkar, N. S.; Bhanage, B. M. *Tetrahedron* **2008**, *64*, 3655.

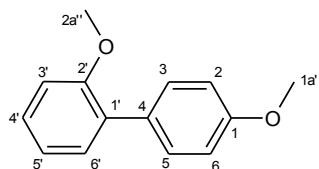
(85%).  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{H}}$ , ppm: 7.43-7.48 (m, 3H), 7.48-7.57 (m, 6H), 7.89 (d,  $J = 8.2$  Hz, 1H), 7.90-7.96 (m, 2H).  $^{13}\text{C}\{^1\text{H}\}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{C}}$ , ppm: 125.3 (C-2), 125.7 (C-4'), 126.0 (C-5), 126.0 (C-4), 126.9 (C-6), 127.2 (C-7), 127.6 (C-8), 128.2 (C-2', 6'), 130.0 (C-3, 3', 5'), 131.6 (C-4a), 133.8 (C-8a), 140.2 (C-1), 140.7 (C-1'). MS (EIMS)  $m/z$  (%): 101 (6), 200 (9), 202 (45), 204 [ $\text{M}^+$ ] (100), 205 [ $\text{M}^+ + 1$ ]. IR (neat): 1596, 1494, 1442, 1431, 1356, 1285, 1186, 1182, 1136, 1125, 1112, 1054, 1028  $\text{cm}^{-1}$ .

#### 5.4.6 Synthesis of 2-phenylanisole (258)



Following general procedure E, 2-(2-methoxyphenyl)benzo-1,3,2-diazaborole (0.20 g, 0.89 mmol) was reacted with bromobenzene **178** (0.50 ml) to afford **258** as a light yellow oil<sup>9,10</sup> (68%):  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{H}}$ , ppm: 3.85 (s, 3H), 7.01-7.10 (m, 2H), 7.33-7.39 (m, 3H), 7.42-7.48 (m, 2H), 7.55-7.60 (m, 2H).  $^{13}\text{C}\{^1\text{H}\}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{C}}$ , ppm: 55.5 (C-1a'), 111.3 (C-6), 120.8 (C-4), 126.9 (C-4'), 127.9 (C-2', 6'), 128.6 (C-5), 129.55 (C-3', 5'), 130.9 (C-3), 130.9 (C-2), 138.5 (C-1'), 156.5 (C-1). MS (EIMS)  $m/z$  (%): 184 [ $\text{M}^+$ ] (100%), 141 (57%), 169 (53%), 115 (39%), 168 (14%), 185 [ $\text{M}^+ + 1$ ] (13%). IR (neat): 2956, 1557, 1514, 1485, 1456, 1402, 1360, 1238, 1125, 1054, 1028  $\text{cm}^{-1}$ .

#### 5.4.7 Synthesis of 4-(2-methoxyphenyl)-anisole (259)

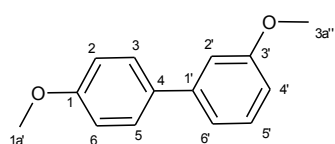


Following general procedure E, 2-(2-methoxyphenyl)benzo-1,3,2-diazaborole (0.20 g, 0.89 mmol) was reacted with 4-bromoanisole **156** (0.50 ml) to afford **259** as a white powder (65%) mp 69-70 °C (lit.<sup>10</sup>: 70-71 °C):  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{H}}$ ,

<sup>10</sup> Qin, C.; Lu, W. *J. Org. Chem.* **2008**, 73, 7424.

ppm: 3.83 (3H, s), 3.87 (s, 3H), 6.94-7.04 (m, 4H), 7.28-7.36 (m, 2H), 7.50 (d,  $J = 8.8$  Hz, 2H).  $^{13}\text{C}\{^1\text{H}\}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{C}}$ , ppm: 55.27 (C-1a'), 55.57 (C-2a'), 111.30 (C-3'), 113.5 (C-2,6), 120.8 (C-5'), 128.1 (C-4'), 130.4 (C-1'), 130.6 (C-3, 5), 130.7 (C-6'), 130.9 (C-4), 156.5 (C-1), 158.7 (C-2'). MS (EIMS)  $m/z$  (%): 214 [ $\text{M}^+$ ] (100%), 199 (56%), 184 (44%), 128 (23%), 215 [ $\text{M}^+ + 1$ ] (15%). IR (neat): 3000, 2956, 2835, 1727, 1596, 1516, 1485, 1463, 1408, 1263, 1239, 1179, 1121, 1106, 1052, 1035, 1017, 1002  $\text{cm}^{-1}$ .

#### 5.4.8 Synthesis of 4-(3-methoxyphenyl)-anisole (**260**)



Following general procedure E, 2-(3-methoxyphenyl)benzo-1,3,2-diazaborole (0.20 g, 0.89 mmol) was reacted with 4-bromoanisole **156** (0.50 ml) to afford **260** as a white powder (76%): mp 58-59 °C (lit.<sup>11</sup>: 58-60 °C):  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{H}}$ , ppm: 3.88 (s, 3H), 3.89 (s, 3H), 6.88 (dd,  $J = 8.1, 1.7$  Hz, 1H), 7.00 (d,  $J = 8.7$  Hz, 2H), 7.10-7.13 (m, 1H), 7.17 (d,  $J = 7.8$  Hz, 1H), 7.36 (t,  $J = 8.0$  Hz, 1H), 7.55 (d,  $J = 8.7$  Hz, 2H).  $^{13}\text{C}\{^1\text{H}\}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{C}}$ , ppm: 55.2 (C-1a'), 55.3 (C-3a'), 112.0 (C-4'), 112.5 (C-2'), 114.1 (C-2, 6), 119.3 (C-6'), 128.4 (C-3, 5), 129.6 (C-5'), 133.6 (C-4), 142.3 (C-1'), 159.2 (C-1), 159.9 (C-3'). MS (EIMS)  $m/z$  (%): 214 [ $\text{M}^+$ ] (100%), 199 (56%), 184 (44%), 128 (23%), 215 [ $\text{M}^+ + 1$ ] (15%). IR (neat): 3003, 2963, 2837, 1727, 1596, 1484, 1464, 1286, 1248, 1240, 1119, 1034  $\text{cm}^{-1}$ .

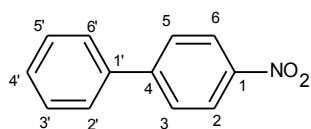
**General Procedure (F):** A microwave tube equipped with a magnetic stirrer bar was charged with the corresponding 2-arylbenzo-1,3,2-diazaborole (1.5 equiv.),  $\text{Pd}(\text{OAc})_2$  (4.0 mol %),  $\text{PCy}_3$  (8.0 mol%) and aryl bromide (1.0 equiv.). The tube was fitted with a rubber septum and continuously purged with argon for 20 minutes. In a separate 10 ml round bottomed flask,  $\text{K}_3\text{PO}_4 \cdot \text{H}_2\text{O}$  (3.0 equiv.) was dissolved in water (0.2 ml) and toluene (1.0 ml) was added. The flask was fitted with a rubber septum and argon was bubbled into the solution for 20 minutes. The content of the round bottom flask was transferred *via* cannula into a microwave tube which was capped and immediately

<sup>11</sup> Itoh, Y.; Brossi, A.; Hamel, E.; Lin, C. M. *Helvetica Chimica Acta* **1988**, 71, 1199.



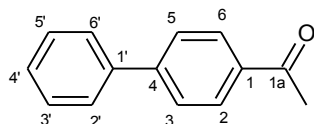
irradiated in a closed vessel with 80W of microwave energy at 100 Psi and 100 °C for 10 minutes. The content of the tube was transferred to a beaker and aqueous hydrochloric acid (2 M, 3.0 ml) was added to hydrolyze excess 2-arylbenzo-1,3,2-diazaborole. The reaction mixture was stirred at room temperature for 10 minutes and the upper black layer was extracted with acetone and concentrated in *vacuo*. The resulting black residue was purified through a short silica column followed by radial chromatography using hexane: ethyl acetate (9:1) as eluting solvent.

### 5.4.9 Synthesis of 4-phenylnitrobenzene (262)



Following general procedure F, 2-phenylbenzo-1,3,2-diazaborole (0.29 g, 1.49 mmol) was reacted with 4-bromonitrobenzene **261** (0.20 g, 0.99 mmol) to afford **262** as colourless crystals (91%) mp 112-114 °C (lit.<sup>12</sup>: 112-115° C): <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>) δ<sub>H</sub>, ppm: 7.43-7.56 (m, 3H), 7.61-7.67 (m, 2H), 7.76 (d, *J* = 8.9 Hz, 2H), 8.32 (d, *J* = 9.0 Hz, 2H). <sup>13</sup>C{<sup>1</sup>H} NMR (100 MHz, CDCl<sub>3</sub>) δ<sub>C</sub>, ppm: 124.0 (C-3', 5'), 127.3 (C-2', 6'), 127.7 (C-3, 5), 128.9 (C-4'), 129.1 (C-2, 6), 138.7 (C-1'), 147.1 (C-1), 147.6 (C-4). MS (EIMS): *m/z* (%): 115 (11), 141 (41), 152 (93), 169 (70), 199 [M<sup>+</sup>] (100), 200 [M<sup>+</sup>+1] (15). IR (neat): 3098, 3078, 1987, 1930, 1593, 1511, 1449, 1404, 1338, 1286, 1103, 1079 cm<sup>-1</sup>.

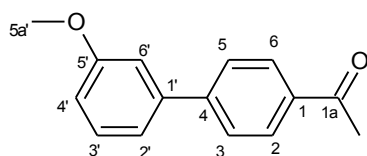
### 5.4.10 Synthesis of 4-phenylacetophenone (264)



<sup>12</sup> Milanesi, S.; Fagnoni, M.; Albini, A. *J. Org. Chem.* **2005**, *70*, 603.

Following general procedure F, 2-phenylbenzo-1,3,2-diazaborole (0.29 g, 1.52 mmol) was reacted with 4-bromoacetophenone **263** (0.20 g, 1.01 mmol) to afford **264** as colourless needle-like crystals (74%): mp 123-124 °C (lit.<sup>13</sup>: 122-124 °C): <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>) δ<sub>H</sub>, ppm: 2.66 (s, 3H), 7.38-7.44 (m, 1H), 7.44-7.52 (m, 2H), 7.65 (d, *J* = 8.2 Hz, 2H), 7.70 (d, *J* = 7.6 Hz, 2H), 8.05 (d, *J* = 7.7 Hz, 2H). <sup>13</sup>C{<sup>1</sup>H} NMR (100 MHz, CDCl<sub>3</sub>) δ<sub>C</sub>, ppm: 26.62 (C(O)CH<sub>3</sub>), 127.2 (C-2', 6'), 127.2 (C-3, 5), 128.2 (C-4'), 128.9 (C-3', 5'), 128.9 (C-2, 6), 135.9 (C-1'), 139.9 (C-4), 145.8 (C-1), 197.6 (C(O)CH<sub>3</sub>). MS (EIMS) *m/z* (%): 181 (100%), 152 (54%), 153 (47%), 196 [M<sup>+</sup>] (41%), 151 (16%), 197 [M<sup>+</sup> + 1] (9%), 154 (6%). IR (neat): 2921, 2853, 1677, 1600, 1559, 1485, 1451, 1423, 1403, 1358, 1282, 1260, 1178, 1121, 1077, 1019 cm<sup>-1</sup>.

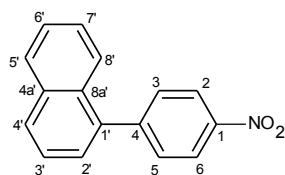
#### 5.4.11 Synthesis of 4-(3-methoxyphenyl)-acetophenone (**265**)



Following general procedure F, 2-(3-methoxyphenyl)benzo-1,3,2-diazaborole (0.30 g, 1.34 mmol) was reacted with 4-bromoacetophenone **263** (0.18 g, 0.89 mmol) to afford **265** as a cream white powder (83%): mp 88-90 °C (lit.<sup>3</sup>: 61-63 °C). <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>) δ<sub>H</sub>, ppm: 2.66 (s, 3H), 3.90 (s, 3H), 6.96 (dd, *J* = 8.4, 2.1 Hz, 1H), 7.17 (s, 1H), 7.23 (d, *J* = 7.6 Hz, 1H), 7.40 (t, *J* = 7.9 Hz, 1H), 7.69 (d, *J* = 8.3 Hz, 2H), 8.04 (d, *J* = 8.2 Hz, 2H). <sup>13</sup>C {<sup>1</sup>H} NMR (100 MHz, CDCl<sub>3</sub>) δ<sub>C</sub>, ppm: 26.61 (C(O)CH<sub>3</sub>), 55.36 (OCH<sub>3</sub>), 113.1 (C-4'), 113.5 (C-2'), 119.7 (C-6'), 127.2 (C-2, 6), 128.8 (C-3, 5), 129.9 (C-5'), 141.4 (C-4), 145.6 (C-1'), 160.0 (C-3'), 197.6 (C(O)CH<sub>3</sub>). MS (EIMS) *m/z* (%): 211 (100%), 226 [M<sup>+</sup>] (53%), 168 (19%), 153 (19%), 139 (15%), 227 [M<sup>+</sup> + 1] (8%). IR (neat): 2934, 2837, 1673, 1591, 1538, 1485, 1464, 1398, 1270, 1217, 1179, 1116, 1029 cm<sup>-1</sup>.

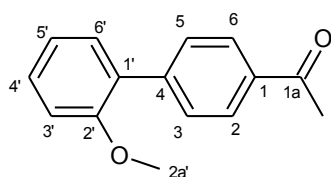
<sup>13</sup> Metallinos, C.; Barrett, F. B.; Chaytor, J. L.; Heska, M. E. A. *Org. Lett.* **2004**, 6, 3641.

### 5.4.12 Synthesis of 1-(4-nitrophenyl)-naphthalene (267)



Following general procedure F, 2-(1-naphthyl)benzo-1,3,2-diazaborole (0.30 g, 1.23 mmol) was reacted with 4-bromonitrobenzene **261** (0.17 g, 0.82 mmol) to afford **267** as colourless crystals (96%): mp 132-133 °C (lit.<sup>7</sup>: 132-133 °C). <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>) δ<sub>H</sub>, ppm: 7.40-7.52 (m, 4H), 7.52-7.62 (m, 2H), 7.69 (d, *J* = 8.8 Hz, 2H), 7.80 (d, *J* = 8.4 Hz, 1H), 7.96 (dd, *J* = 7.8, 2.9 Hz, 2H), 8.38 (d, *J* = 8.8 Hz, 2H). <sup>13</sup>C{<sup>1</sup>H} NMR (100 MHz, CDCl<sub>3</sub>) δ<sub>C</sub>, ppm: 123.5 (C-3, 5), 125.1 (C-2'), 125.3 (C-7'), 126.2 (C-6'), 126.73 (C-5'), 127.0 (C-4'), 128.5 (C-8'), 128.9 (C-3'), 130.9 (C-2, 6), 130.9 (C-4a'), 133.8 (C-8a'), 137.8 (C-1'), 147.2 (C-1), 147.6 (C-4). MS (EIMS) *m/z* (%): 202 (100%), 249 [M<sup>+</sup>] (95%), 203 (59%), 203 (41%), 200 (14%), 201 (19%), 219 (16%), 250 [M<sup>+</sup> + 1] (13%). IR (neat): 2929, 1937, 1723, 1596, 1513, 1395, 1346, 1311, 1285, 1250, 1106, 1015 cm<sup>-1</sup>.

### 5.4.13 Synthesis of 4-(2-methoxyphenyl)-acetophenone (268)

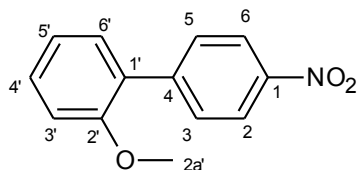


Following general procedure F, 2-(2-methoxyphenyl)benzo-1,3,2-diazaborole (0.30 g, 1.34 mmol) was reacted with 4-bromoacetophenone **263** (0.18 g, 0.89 mmol) to afford **268** as a white powder (90%): mp 105-107 °C (lit.<sup>14</sup>: 106-107 °C). <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>) δ<sub>H</sub>, ppm: 2.66 (s, 3H), 3.84 (s, 3H), 7.02-7.09 (m, 2H), 7.33-7.41 (m, 2H), 7.65 (d, *J* = 8.6 Hz, 2H), 8.02 (d, *J* = 8.4 Hz, 2H). <sup>13</sup>C{<sup>1</sup>H} NMR (100 MHz, CDCl<sub>3</sub>) δ<sub>C</sub>, ppm: 26.5 (C(O)CH<sub>3</sub>), 55.5 (OCH<sub>3</sub>), 111.4 (C-3'), 120.9 (C-5'), 128.06

<sup>14</sup> Quasdorf, W. K.; Riecher, M.; Petrova, V. K. Garg, K. N. *J. Am. Chem. Soc.* **2009**, *131*, 17748.

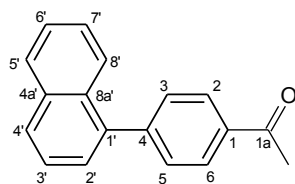
(C-3, 5), 129.4 (C-4'), 129.7 (C-2, 6), 130.7 (C-6'), 135.5 (C-1), 143.6 (C-4), 156.5 (C-2'), 197.8 ( $\underline{C}(O)CH_3$ ). MS (EIMS)  $m/z$  (%): 211 (100%), 168 (63%), 226 [ $M^+$ ] (54%), 139 (19%), 227 [ $M^+ + 1$ ] (11%), 160 (9%), 152 (6%). IR (neat): 3001, 2956, 2833, 1670, 1601, 1456, 1265, 1238, 1186, 1166, 1003  $cm^{-1}$ .

#### 5.4.14 Synthesis of 4-(2-methoxyphenyl)-nitrobenzene (**269**)



Following general procedure F, 2-(2-methoxyphenyl)benzo-1,3,2-diazaborole **3** (0.30 g, 1.34 mmol) was reacted with 4-bromonitrobenzene **261** (0.18 g, 0.89 mmol) to afford **269** as a white powder (0.17 g, 85%): mp 62-63 °C (lit.<sup>3</sup>: 61-63 °C).  $^1H$  NMR (400 MHz,  $CDCl_3$ )  $\delta$ : 3.86 (s, 3H), 7.02-7.11 (m, 2H), 7.35 (dd,  $J = 7.5, 1.7$  Hz, 1H), 7.38-7.45 (m, 1H), 7.71 (d,  $J = 8.8$  Hz, 2H), 8.20 (d,  $J = 8.8$  Hz, 2H).  $^{13}C\{^1H\}$  NMR (100 MHz,  $CDCl_3$ )  $\delta$ : 55.5 ( $OCH_3$ ), 111.4 (C-3'), 121.1 (C-5'), 123.1 (C-3, 5), 128.3 (C-1), 130.1 (C-4'), 130.3 (C-2, 6), 130.6 (C-6'), 145.4 (C-4), 146.6 (C-2), 156.4 (C-2'). MS (EIMS)  $m/z$  (%): 229 [ $M^+$ ] (100%), 139 (53%), 152 (28%), 128 (21%), 230 [ $M^+ + 1$ ] (10%). IR (neat): 2962, 2937, 2836, 1601, 1510, 1480, 1456, 1346, 1231, 1177, 1123, 1022, 1005  $cm^{-1}$ .

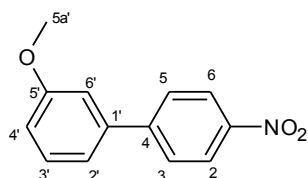
#### 5.4.15 Synthesis of 1-[4-(1-naphthalenyl)]-ethanone (**271**)



Following general procedure F, 2-(1-naphthyl)benzo-1,3,2-diazaborolidine (**183**) (0.30 g, 1.23 mmol) was reacted with 4-bromoacetophenone **263** (0.16 g, 0.82 mmol) to afford **271** as colourless crystals (0.19 g, 94%) mp 102-103 °C (lit.<sup>7</sup>: 102-103 °C):  $^1H$  NMR (400 MHz,  $CDCl_3$ )  $\delta_H$ , ppm: 2.70 (s, 3H), 7.42-7.50 (m, 2H), 7.50-7.60 (m,

2H), 7.63 (d,  $J = 8.3$  Hz, 2H), 7.86 (d,  $J = 8.4$  Hz, 1H), 7.93 (t,  $J = 9.5$  Hz, 2H), 8.11 (d,  $J = 8.5$  Hz, 2H).  $^{13}\text{C}\{^1\text{H}\}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{C}}$ , ppm: 26.6 ( $\text{C}(\text{O})\underline{\text{C}}\text{H}_3$ ), 125.3 (C-2'), 125.5 (C-5'), 125.9 (C-4'), 126.3 (C-8'), 126.9 (C-3'), 128.35 (C-7'), 128.41 (C-6'), 130.31 (C-5), 131.2 (C-1), 133.8 (C-8a'), 136.0 (C-4), 139.0 (C-1'), 145.81 ( $\text{C}(\text{O})\underline{\text{C}}\text{H}_3$ ). MS (EIMS)  $m/z$  (%): 231 (100%), 246 [ $\text{M}^+$ ] (72%), 202 (64%), 203 (41%), 247 [ $\text{M}^+ + 1$ ] (14%), 201 (12%). IR (neat): 2923, 2852, 1681, 1604, 1589, 1504, 1396, 1356, 1309, 1268, 1255, 1181, 1112, 1016  $\text{cm}^{-1}$ .

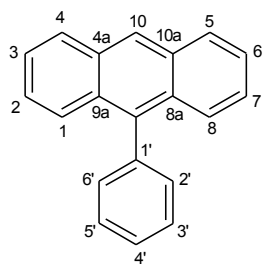
#### 5.4.16 Synthesis of 4-(3-methoxyphenyl)-nitrobenzene (**272**)



Following general procedure F, 2-(3-methoxyphenyl)benzo-1,3,2-diazaborole (0.30 g, 1.34 mmol) was reacted with 4-bromonitrobenzene **261** (0.18 g, 0.89 mmol) to afford **272** as white crystals (91%): mp 86-87 °C (lit.<sup>15</sup>: 86-87 °C).  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{H}}$ , ppm: 3.90 (s, 3H), 7.00 (dd,  $J = 8.1, 2.3$  Hz, 1H), 7.13-7.7.17 (m, 1H), 7.19-7.24 (m, 1H), 7.43 (t,  $J = 8.0$  Hz, 1H), 7.74 (d,  $J = 8.8$  Hz, 2H), 8.31 (d,  $J = 8.9$  Hz, 2H).  $^{13}\text{C}\{^1\text{H}\}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{C}}$ , ppm: 55.4 (C-5a'), 113.2 (C-4'), 114.1 (C-2'), 119.8 (C-6'), 124.0 (C-3,5), 127.8 (C-2, 6), 130.2 (C-5'), 140.2 (C-4), 147.2 (C-1), 147.4 (C-1'), 160.1 (C-3'). MS (EIMS)  $m/z$  (%): 229 [ $\text{M}^+$ ] (100%), 139 (53%), 171 (49%), 199 (48%), 140 (42%), 152 (28%), 128 (21%), 230 [ $\text{M}^+ + 1$ ] (10%). IR (neat): 2947, 2842, 1585, 1508, 1468, 1430, 1342, 1325, 1304, 1292, 1188, 1160, 1020  $\text{cm}^{-1}$ .

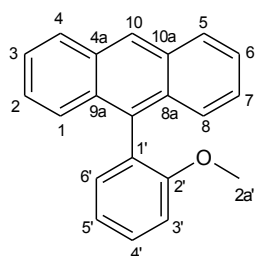
<sup>15</sup> Seganish, W. M.; DeShong, P. *J. Org. Chem.* **2004**, *69*, 6790.

### 5.4.17 Synthesis of 9-phenylanthracene (277)



Following general procedure F, 2-phenylbenzo-1,3,2-diazaborole (**178**) (0.29 g, 1.49 mmol) was reacted with 9-bromoanthracene (**273**) (0.26 g, 0.99 mmol) to afford **277** as colourless plates-like crystals (0.19 g, 75%): mp 155-157 °C (lit.<sup>16</sup>: 153-155 °C). <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>)  $\delta_{\text{H}}$ , ppm: 7.32-7.42 (m, 2H), 7.42-7.53 (m, 4H), 7.53-7.65 (m, 3H), 7.70 (d,  $J$  = 8.79 Hz, 2H), 8.07 (d,  $J$  = 8.45 Hz, 2H), 8.52 (s, 1H). <sup>13</sup>C{<sup>1</sup>H} NMR (100 MHz, CDCl<sub>3</sub>)  $\delta_{\text{C}}$ , ppm: 125.1, 125.3, 126.5, 126.8, 127.4, 128.3, 128.3, 130.2, 131.2, 131.3, 137.0, 138.8. MS (EIMS)  $m/z$  (%): IR (neat): 3051, 2923, 1596, 1494, 1442, 1411, 1357, 1312, 1220, 1166, 1015 cm<sup>-1</sup>.

### 5.4.18 Synthesis of 9-(2-methoxyphenyl)-anthracene (275)



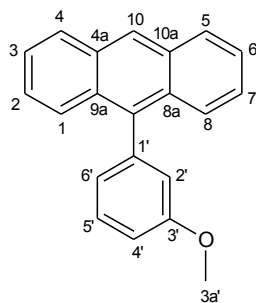
Following general procedure F, 2-(2-methoxyphenyl)benzo-1,3,2-diazaborole (0.30 g, 1.34 mmol) was reacted with 9-bromoanthracene **275** (0.26 g, 0.99 mmol) to afford **275** as cream-white powder (0.20 g, 72%): mp 177-178 °C (lit.<sup>17</sup>: 177-179 °C). <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>)  $\delta_{\text{H}}$ , ppm: 3.67 (s, 3H), 7.19-7.30 (m, 2H), 7.36-7.485 (m, 3H), 7.53 (t,  $J$  = 7.0 Hz, 2H), 7.58-7.65 (m, 1H), 7.75 (d,  $J$  = 8.7 Hz, 2H), 8.12 (d,  $J$  = 8.3 Hz, 2H), 8.55 (s, 1H). <sup>13</sup>C {<sup>1</sup>H} NMR (100 MHz, CDCl<sub>3</sub>)  $\delta_{\text{C}}$ , ppm: 55.7, 111.36, 120.7, 125.0, 125.2, 126.5, 126.7, 127.3, 128.4, 129.3, 130.4, 131.4, 132.8, 133.7,

<sup>16</sup> Nakamichi, N.; Kawabota, H.; Hayashi, M. *J. Org. Chem.* **2003**, 68, 8272.

<sup>17</sup> Yoshida, T.; Hiroyuku, W.; Michiyo, N.; Tetsuya, S.; Masahiro, M.; Masakatsu, N. *J. Org. Chem.* **2003**, 68, 5236.

158.0. MS (EIMS)  $m/z$  (%): 119 (10), 126 (5), 178 (20), 191 (10), 239 (36), 284 [ $M^+$ ] (100), 285 [ $M^++1$ ] (16). IR (neat): 1805, 1597, 1493, 1462, 1431, 1356, 1242, 1220, 1108, 1047, 1019  $\text{cm}^{-1}$ .

#### 5.4.19 Synthesis of 9-(3-methoxyphenyl)-anthracene (**276**)



Following general procedure F, 2-(3-methoxyphenyl)benzo-1,3,2-diazaborole (0.30 g, 1.34 mmol) was coupled with 9-bromoanthracene **273** (0.26 g, 0.99 mmol) to afford **276** as colourless crystals (69%): mp 99-101 °C (lit.<sup>18</sup>: 99-100 °C).  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{H}}$ , ppm: 3.92 (s, 3H), 7.13-7.21 (m, 3H), 7.33-7.41 (m, 2H), 7.44-7.55 (m, 3H), 7.73 (d,  $J$  = 8.8 Hz, 2H), 8.06 (d,  $J$  = 8.4 Hz, 2H), 8.51 (s, 1H).  $^{13}\text{C}\{^1\text{H}\}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{C}}$ , ppm: 55.3, 113.2, 116.6, 123.7, 125.1, 125.3, 126.5, 126.8, 128.2, 129.3, 130.1, 131.3, 136.8, 140.2, 159.6. MS (EIMS)  $m/z$  (%): IR (neat): 3049, 3005, 1595, 1582, 1459, 1238, 1156, 1039, 1013  $\text{cm}^{-1}$ .

<sup>18</sup> Dikerman, C. S.; Klein, M. V.; George, B. *J. Org. Chem.* **1964**, *29*, 3695.